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Executive Summary

Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California

Hashem Akbari, L. Shea Rose, and Haider Taha

Heat Island Group
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

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Abstract

To estimate the impact of light-colored surfaces (roofs and pavements) and urban vegetation (trees, grass, shrubs) on meteorology and air quality of a city, it is essential to accurately characterize various urban surfaces. Of particular importance is the characterization of the area fraction of various surface-types, as well as the vegetative fraction. In this report, a method is discussed for developing data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color photography. We devised a semi-automatic Monte-Carlo method to sample the data and visually identify the surface-type for each pixel. The color aerial photographs for Sacramento covered a total of about 65 square km (25 square mile). At 0.30-m resolution, there were approximately $7x10^8$ pixels of data.

Five major land-use types were examined: 1) downtown and city center, 2) industrial, 3) offices, 4) commercial, and 5) residential. In downtown Sacramento, the top view (above the canopy) shows that vegetation covers 30% of the area, whereas roofs cover 23% and paved surface (roads, parking areas, and sidewalks) 41%. Under-the-canopy fabric consists of 52% paved surfaces, 26% roofs, and 12% grass. In the industrial areas, vegetation covers 8-14% of the area, whereas roofs cover 19-23%, and paved surfaces cover 29-44%. The surface-type percentages in the office area were 21% trees, 16% roofs, and 49% paved surfaces. In commercial areas, vegetation covers 5-20%, roofs 19-20%, paved surfaces 44-68% (about 25-54% are parking areas). Residential areas exhibit a wide range of percentages of surface-types. On average, vegetation covers about 36% of the area (ranging 32-49%), roofs cover about 20% (ranging 12-25%), and paved surfaces about 28% (ranging 21-34%). Trees mostly shade streets, parking lots, grass, and sidewalks. Under the canopy the percentage of paved surfaces is significantly higher. In most non-residential areas, paved surfaces cover 50-70% of the area. In residential areas, on average, paved surfaces cover about 35% of the area.

Land-use/land-cover (LULC) data from the United States Geological Survey was used to extrapolate these results from neighborhood scales to metropolitan Sacramento. In an area of roughly $800km^2$, defining most of metropolitan Sacramento, about half is residential. The total roof area is about $150km^2$ and the total paved surfaces (roads, parking areas, side walks) is about $310km^2$. The total vegetated area is about $230km^2$.

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[1] This work was supported by the U. S. Environmental Protection Agency through the U. S. Department of Energy under contract DE-AC03-76SF00098.

Acknowledgements

This work was supported by the U. S. Environmental Protection Agency under the Urban Heat Island Pilot Project (UHIPP) through the U. S. Department of Energy under contract DE-AC03-76SF00098. We acknowledge the support and guidance from Virginia Gorsevski and Jeanne Briskin of the EPA. Brian Pon helped us with graphics.

Executive Summary

The Heat Island Reduction Initiative (HIRI) is a joint program sponsored by the U.S. Environmental Protection Agency (EPA) and the Department of Energy (DOE) to encourage the use of strategies designed to reduce demand for cooling energy use and prevent smog formation. As part of the initiative, the Urban Heat Island Pilot Project (UHIPP) was launched to quantify the potential impacts of heat island reduction strategies in terms of energy savings, economic benefits, and air-quality improvements. Sacramento, CA, Salt Lake City, UT, and Baton Rouge, LA were selected for the UHIPP. Since the inception of the project, LBNL has conducted detailed studies to investigate the impact of mitigation technologies on heating and cooling energy use in the three pilot cities. In addition, LBNL has collected urban surface characteristics data and conducted meteorology and urban smog simulations for the three pilot cities.

One of the components of UHIPP research activities is to analyze the fabric of the pilot cities by accurately characterizing various surface components, This is important since the fabric of the city is directly relevant to the design and implementation of heat-island reduction strategies. Of particular importance is the characterization of the area fraction of various surface types as well as vegetative cover. Accurate characterization of the urban fabric would allow the design of implementation programs with a better assessment of the cost and benefits of program components. In addition, the results of such detailed analysis will be used in simulating the impact of heat-island reduction strategies on local meteorology and air quality.

In this report, a method is discussed for developing high-quality data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color photography. This method is applied to obtain the fabric of Sacramento, California as a case study.

The color aerial photographs of Sacramento covered a total of about 65 square km (25 square mile). **Picture EX.1** depicts a sample photograph of downtown Sacramento. At 0.30-m resolution, there were approximately $7\text{x}10^8$ pixels of data. We devised a semi-automatic method to sample the data and visually identify the surface-type for each pixel. The method involves four steps:

- Visual inspection of aerial photographs and preparation of a list of various surface-types identifiable in the photos;
- Grouping of surface categories into major types;
- Random sampling a subset of data for each region (through a Monte-Carlo sampling approach), and visual inspection of each sample and the assignment of a surface classification to it (these surface classifications is summarized in **Table EX.1**); and
- Extrapolation of the results to the entire Sacramento regional area, using the United States Geological Survey (USGS) land-use/land-cover (LULC) data as a basis.

The classification in Table EX.1 may include more detail than necessary (even more details can be seen in the photos, for example, mailboxes, small benches, etc., that are, of course, irrelevant to this task). A distinction was made between Category 1, "Unidentified", and Category 30, "Other Feature". Those surfaces classified as "Unidentified" could not be

Table EX.1. Visually identifiable features of interest in the Sacramento region (based on aerial photographs).

Category	Description	Category	Description
1	Unidentified	16	Swimming Pool
2	Tree Covering Roof	17	Auto Covering Road
3	Tree Covering Road	18	Private Paved Surfaces
4	Tree Covering Sidewalk	19	Parking Deck
5	Tree Covering Parking	20	Alley
6	Tree Covering Grass	21	Water
7	Tree Covering Dry/Barren Land	22	Grass on Roof
8	Tree Covering Other	23	Train Tracks
9	Tree Covering Alley	24	Auto Covering Parking
10	Roof	25	Recreational Surface
11	Road	26	Residential Driveway
12	Sidewalk	27	Awning
13	Parking Area	28	Channel Road
14	Grass	29	Channel Land
15	Dry/Barren Land	30	Other Feature (not of interest)

accurately defined, while those in the "Other Feature" category could be, but were not relevant to this study. This distinction was necessary to avoid assigning the known features incorrectly.

The various tree categories (Categories 2-9) were later grouped under one category (designated as "Trees"). For meteorological modeling purposes, one tree category is sufficient to determine the fraction of vegetation in the urban area. However, for implementation purposes, one would like to "see" what lies beneath the canopy of trees. Thus in this case the areas beneath the trees are simply totaled and the tree canopy ignored, assuming trunk area is negligible. As shown in **Table EX.2**, categories of related surface-types were grouped in representative types for an "above-the-canopy" perspective. The grouping was done in order to aggregate similar surfaces that may also have similar albedos.[2] For instance, the "Sidewalk" surface-type is the total of the "Residential Driveway" and "Sidewalk" categories since in the areas analyzed, these categories both appeared to be light-colored concrete. "Parking Area" is the total of parking lots and decks, "Grass" is the total of ground-level grass and roof grass, and the category "Miscellaneous" is the total of sporadic surface-types such as swimming pools, water, alleys, autos, private surfaces, and train tracks. For characterization of the surfaces "under-the-canopy," the primarily criteria for grouping was the the function or use of the surface-type. For instance, the under-the-canopy "Roof" category include: "Tree Covering Roof" (Cat. 2), "Roof" (Cat. 10), "Parking Deck" (Cat. 19), "Grass on Roof" (Cat. 22), and "Awning" (Cat. 27). Table EX.2 also shows the assignment of various categories (identified in Table EX.1) to surface-types under the canopy. Under-the-canopy characterization also includes a new general category, "Private Paved Surfaces," to distinguish between public surfaces and those surfaces owned privately. The "Tree Cover" category was eliminated, since at the ground level there is no tree canopy.

Table EX.2. Major surface-types

Surface-Type	Categories included*	Surface-Type	Categories included
	Above-the-canopy view		
Roof	10, 27	Tree Cover	2-9
Road	11, 28	Grass	6, 14
Parking Area	13, 19	Barren Land	15, 29
Sidewalk & Driveway	12, 26	Miscellaneous	16-18, 20, 21, 23-25, 30
	Under-the-canopy view		
Roof	2, 10, 19, 22, 27	Private Paved Surfaces	18, 26
Road	3, 9, 11, 17, 20, 28	Grass	6, 14
Parking Area	5, 13, 24	Barren Land	7, 15, 29
Sidewalk	4, 12	Miscellaneous	8, 16, 21, 23, 25, 30

* Surface-type categories are defined in Table EX.1.

Results from this analysis suggest several possible land-use and surface-type classification schemes for the Sacramento area. In this study, the following five major land-use types are examined: 1) downtown and city center, 2) industrial, 3) offices, 4) commercial, and 5) residential categories. Fourteen different areas were selected for this analysis. For each of these areas, up to 30 different surface-types were identified and their fractional areas computed. The results are shown in **Figures EX.1** (above-the-canopy view of the city) and **EX.2** (under the tree canopy). In downtown Sacramento, the top view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 30% of the area, whereas roofs cover 23% and paved surfaces (roads, parking areas, and sidewalks) 41%. The under-the-canopy fabric consists of 52% paved surfaces, 26% roofs, and 12% grass. In industrial areas, vegetation covers 8-14% of the area,

[2] When sunlight hits an opaque surface, some of the energy is reflected (this fraction is called albedo = a) and the rest is absorbed (the absorbed fraction is 1-a). Low-a surfaces of course become much hotter than high-a surfaces.

whereas roofs cover 19-23%, and paved surfaces cover 29-44%. The surface-type percentages in the office area were 21% trees, 16% roofs, and 49% paved surfaces. In commercial areas, vegetation covers 5-20%, roofs 19-20%, paved surfaces 44-68% (about 25-54% are parking areas). Residential areas exhibit a wide range of surface-types percentages. their various surface-types. On average, vegetation covers about 36% of the area (ranging from 32% to 49%), roofs cover about 20% (ranging from 12% to 25%), and paved surfaces cover about 28% (ranging from 21% to 34%). The wide range of surface-type percentages in many of the land-use categories demonstrates their site-specific nature. Therefore, it is especially difficult to account for the variation between similar land-uses in different areas in most traditional land-use/land-cover classification systems.

Trees mostly shade the streets, parking lots, grass, and sidewalks. Under the canopy, the percentage of paved surfaces is significantly higher (see Figure EX.2). In most non-residential areas, paved surfaces cover 50-70% of the area. In residential areas, on the average, paved surfaces are about 35% of the area.

In order to extrapolate these results from neighborhood to regional scales, e.g., regional Sacramento, land-use/land-cover (LULC) data from the United States Geological Survey (USGS) was used as a basis for mapping the area distributions. In this method, the Sacramento LULCs were mapped onto to those of the USGS and the total areas of surface-types were calculated for the entire region of interest. For an area of roughly 800km^2, defining most of metropolitan Sacramento, about half is residential (see **Figure EX.3a**). The total roof area, as seen from above the canopy, comprises about 19% of the urban area (about 150km^2), total paved surfaces (roads, parking areas, sidewalks) 39% (about 310km^2), and total vegetated area about 28% (230km^2) (see **Figure EX.3b**). The actual total roof area, as seen under the canopy, comprises about 20% of the urban area (about 160km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) 45% (about 360km^2), and total vegetated area (only grass and bushes) is about 20% (160km^2) (see **Figure EX.3c**).

Sacramento is a fairly green city, but the potential for additional urban vegetation is large. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, 30% of parking areas, they would add up to about an additional 15% tree cover for the entire city. A 15% additional tree cover is about 120km^2 of the urban area. Assuming that an average tree can have a horizontal cross-section of about 50 m^2, this calculations suggest a potential for 24 million additional trees in Sacramento. As climate and air-quality simulations have indicated, 24 million additional trees can have a significant impact on cooling Sacramento and improving ozone air quality.

The potential for increasing the albedo of Sacramento is also large. Impermeable surfaces (roofs and pavements) amount to 56% of the total area of Sacramento. For illustration proposes, if we assume that the albedo of the residential roofs can increase by 0.2, commercial roofs by 0.3, roads and parking areas by 0.15, and sidewalks by 0.1, the albedo of urban area of Sacramento can then be increased by about 16% (0.16). Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

These results are based on a limited analysis for one city. In Sacramento there is a significant variation in the fabric of the neighborhoods selected for this analysis. Although an attempt was made to select neighborhoods that represent the variation in the overall communities, these results should not be extrapolated to other cities and regions. Many cities are unique in terms of land-use patterns and constructions (e.g. most urban homes in the west coast are single story as opposed to two-story houses in the east). It is recommended that a similar analysis for several other cities in different regions of the country be performed in order to expand our understanding of the fabric of the city.

Picture EX.1. Aerial photo of downtown Sacramento at 1-foot resolution.

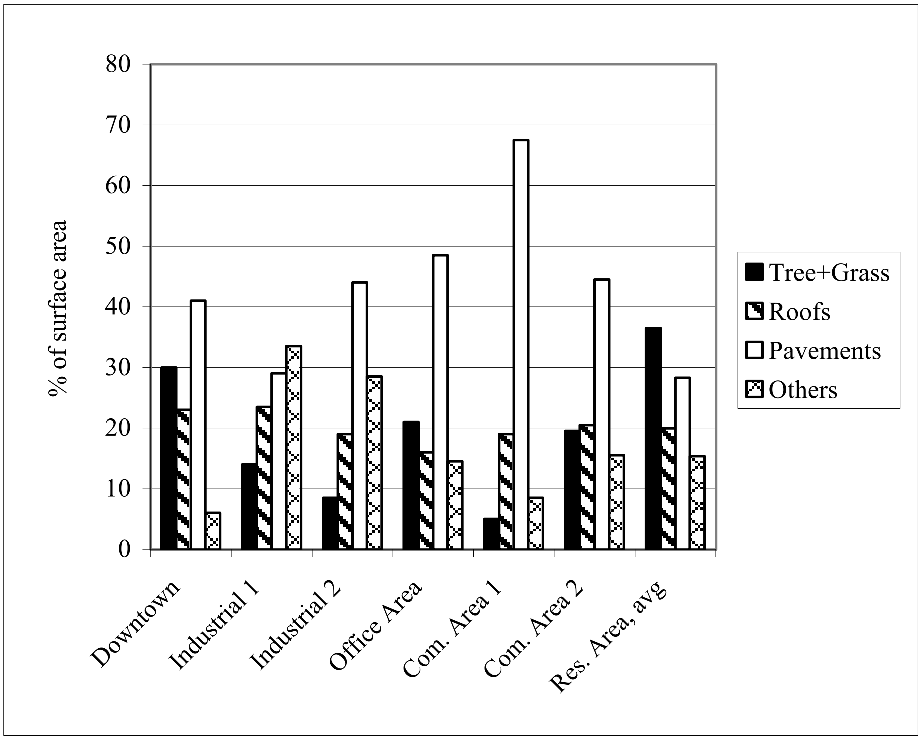

Figure Ex2.a Above the Canopy Fabric of Sacramento, CA

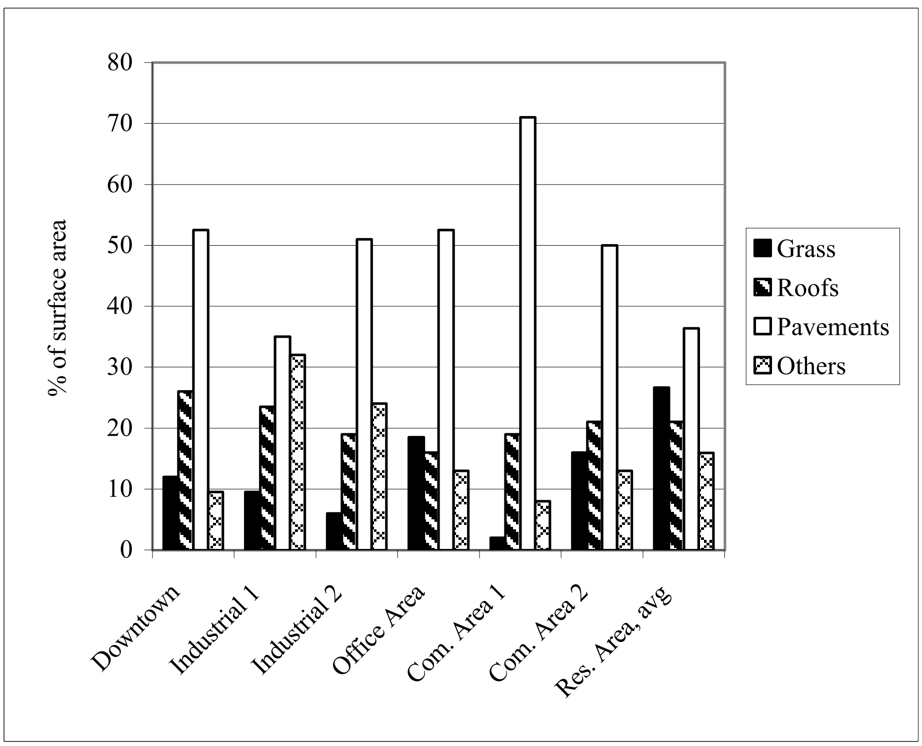

Figure Ex2.b. Under the Canopy Fabric of Sacramento, CA

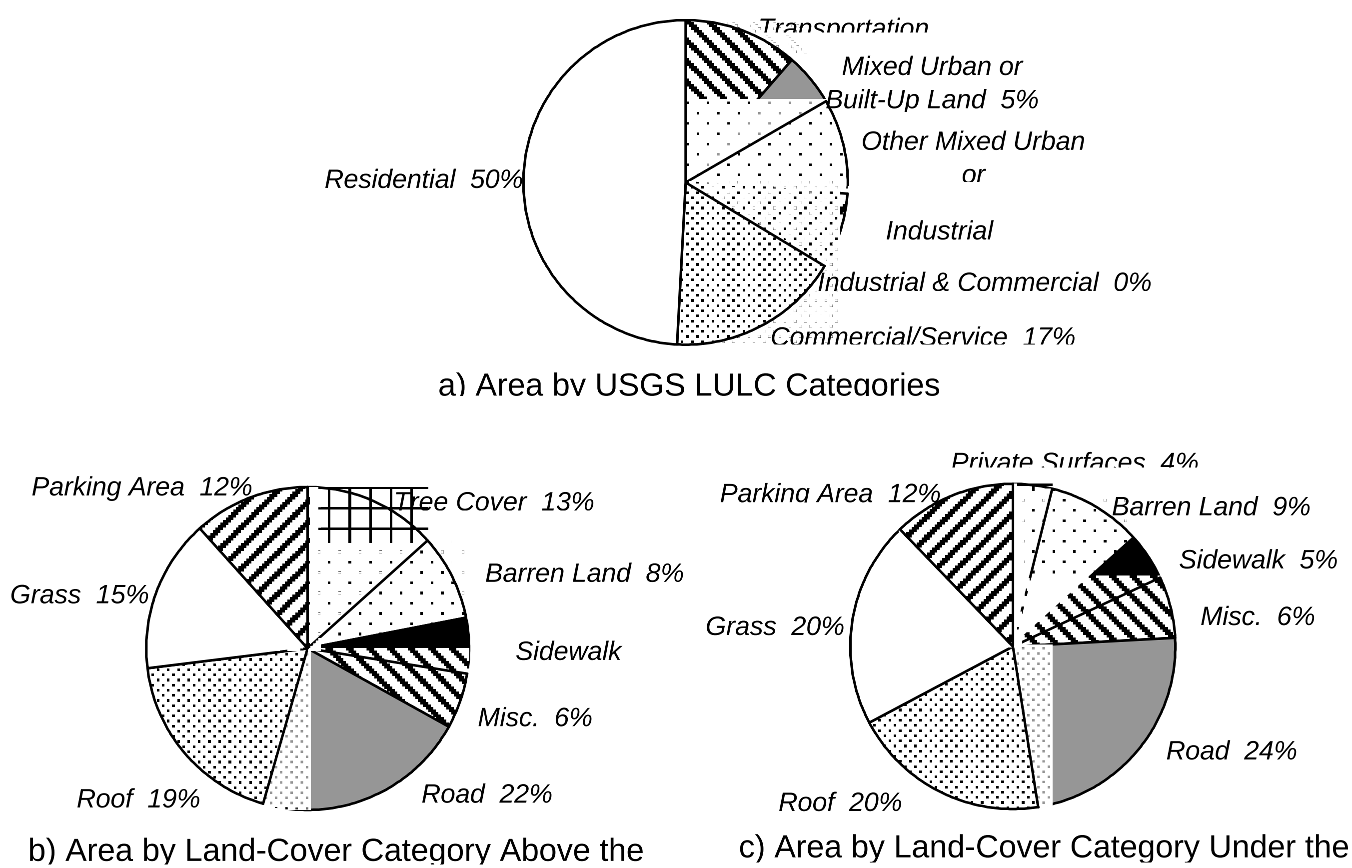

Figure EX.3. Land use/land cover of the entire developed area of Sacramento, CA.

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1. Introduction

The Heat Island Reduction Initiative (HIRI) is a joint program sponsored by the U.S. Environmental Protection Agency (EPA) and the Department of Energy (DOE) to encourage the use of strategies designed to reduce demand for cooling energy use and prevent smog formation in U.S. cities. As part of the initiative, the Urban Heat Island Pilot Project (UHIPP) was launched to quantify the potential impacts of heat-island reduction strategies in terms of energy savings, economic benefits, and air-quality improvements. Sacramento, CA, Salt Lake City, UT, and Baton Rouge, LA were selected for the UHIPP. Since the inception of the project, LBNL has conducted detailed studies to investigate the impact of mitigation technologies on heating and cooling energy use in the three pilot cities. In addition, LBNL has collected urban surface characteristics data and conducted meteorology and urban smog simulations for the three pilot cities.

One of the components of UHIPP research activities is to analyze the fabric of the pilot cities by accurately characterizing various surface components. This is important since the fabric of the city is directly relevant to the design and implementation of heat-island reduction strategies. Of particular importance is the characterization of the area fraction of various surface-types. These data are required to model and analyze the impact of heat-island mitigation measures in reducing energy consumption and improving air quality. Thus, it is important to characterize the surface as accurately as possible, particularly in terms of surface-type distribution and vegetative fraction. An accurate characterization of the surface will allow a better estimate of the potential for increasing surface albedo[3] (roofs, pavements) and urban vegetation. This would in turn provide more accurate modeling of the impact of heat-island reduction measures on ambient cooling and urban smog air quality.

Researchers involved in the analysis of urban climate have tried to estimate the composition of various urban areas. One such work is the analysis of the urban fabric in Sacramento, CA by Myrup and Morgan (1972). They applied the strategy of examining the city data in progressively smaller integral segments of macro-scale (representative areas of Sacramento), meso-scale (individual communities), micro-scale (land-use ordinance zones), and basic-scale (city blocks). The data they used included USGS photos, parks and recreation plans, city engineering roadways, and detailed aerial photos. Their analysis covered 195 square km (76 square miles) of urban areas. The percentages of the land-use areas were calculated as follows: residential 35.5%, commercial 7.2%, industrial 13.5%, streets and freeways 17.0%, institutional 3.2%, and open space and recreational 23.6%. They found the average residential area to be about 22% streets, 23% roofs, 22% other impervious surfaces, and 33% green areas. Overall, for the city, they found 14% streets, 22% roofs, 22% other impervious surfaces, 36% green areas, and 3% water surfaces. They defined "other impervious surfaces" to include highway shoulder strips, airport runways, and parking lots. Streets included curbs and sidewalks.

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[3] When sunlight hits an opaque surface, some of the energy is reflected (this fraction is called albedo = a) and the rest is absorbed (the absorbed fraction is 1-a). Low-a surfaces of course become much hotter than high-a surfaces.

The objective of this study is to develop a high-quality data base of surface-type and city-fabric makeup (% of area covered by various surfaces) for various land-uses in each pilot city selected by the EPA for the UHIPP. An effort is made to develop a method that automates (objective analysis) most of this process to obtain accurate results in an efficient, reproducible manner.

In this report, we first discuss publicly available data sources that can be used to obtain urban fabric. We subsequently present our method for analysis of aerial colored photography of Sacramento, CA. The discussion also includes the arrangements made to obtain the digital aerial data. We apply the method to several representative areas in Sacramento and obtain urban surface characteristics data. Results for the analysis of representative areas are used to estimate the fabric of regional Sacramento (for use in meteorological and air-quality modeling). We conclude the report by providing suggestions and recommendations for future work.

2. Review of Available Data Sources

Initially, a variety of available data sources was considered in analyzing the fabric of the UHIPP cities. Some of these data were obtained from NASA remote sensing platforms, others from satellite or high-altitude aircraft, and a third group from high-resolution cameras flown at low altitudes.

2.1 Advanced Thermal and Land Applications Sensor (ATLAS)

Advanced Thermal and Land Applications Sensor (ATLAS) is used by NASA to collect high-resolution radiometric data in 15 channels. This sensor is typically mounted on a specially-equipped Learjet aircraft flying at about 5km above ground level over the regions of interest. At that altitude, the typical resolution is of ATLAS data 10m. The 15 channels (bands) of ATLAS basically incorporate bands from Landsat TM (Thematic Mapper) (along with several additional channels) and 6 thermal infrared (IR) channels similar to those available on the airborne Thermal Infrared Multispectral Scanner (TIMS) sensor. **Table 1** summarizes the band ranges in ATLAS.

In order to import, analyze, and process the data generated by ATLAS, standard software for raster geographic information systems, Erdas Imagine, was used. To assess the usefulness of ATLAS in the city-fabric analysis, data previously obtained for Atlanta, GA, was used.

Areas that could be identified visually in the ATLAS data images for Atlanta were selected first. These areas were homogeneous and clearly identifiable, e.g., major highways, stadiums, parking lots, and airports. These were used in "truthing" the data since their large features provided the homogeneous samples needed, that is, several 10-m pixels of ATLAS data. Most of these large and homogeneous samples were urban and building surfaces in the downtown area and thus could be rather easily assigned to their respective class: concrete, light-colored roof, dark-colored roof, grass, other vegetation, dark-colored pavement, or light-colored pavement.

Following the initial screening, the brightness values (i.e. the radiation count) in the various bands were analyzed. For each sample area, there is typically a characteristic spectral curve

Table 1. Description of ATLAS bands.

Spectrum	Channel	Bandwidth (μm)
Visible	1	0.45-0.52
	2	0.52-0.60
	3	0.60-0.63
	4	0.63-0.69
	5	0.69-0.76
NIR	6	0.76-0.90
	7	1.55-1.75
	8	2.08-2.35
Infrared	9	3.35-4.20
	10	8.20-8.60
	11	8.60-9.00
	12	9.00-9.40
	13	9.60-10.2
	14	10.2-11.2
	15	11.2-12.2

across the bands (referred to as a "spectral signature"). The spectral signature's minimum and maximum values in each band in a homogeneous sample area were used to set the limits for a parallelepiped classification (A parallelepiped classification is one in which minimum and maximum values of the bands of the spectral signatures that are characteristics of features of interest are used to classify a dataset [ERDAS 1997]). If the range of data in all bands of a particular data point, or pixel, fell between the minimum and maximum values for a particular sample area, it was assigned to the same class as the sample area. This process was repeated several times using different samples, changing the classification order, and by combining similar sample areas for the classes, until a majority of the area was accurately classified (e.g., downtown Atlanta was classified as shown in **Figure 1**).

Unfortunately, this process did not produce satisfactory results in the residential neighborhoods. There are two reasons for this: 1) the areas of the various surface components were finer (smaller) than ATLAS 10-m resolution (each pixel covers 100 m^2 of area), and 2) other types of surfaces did not fit in any signature classification. Since no residential features were clearly visible in the ATLAS data images, none of the classes produced satisfactory results. The resolution (pixel size) limits this type of classification since the features of interest vary in area from the size of a single tree to the area of a roof. Therefore, most of the pixels in the residential areas are

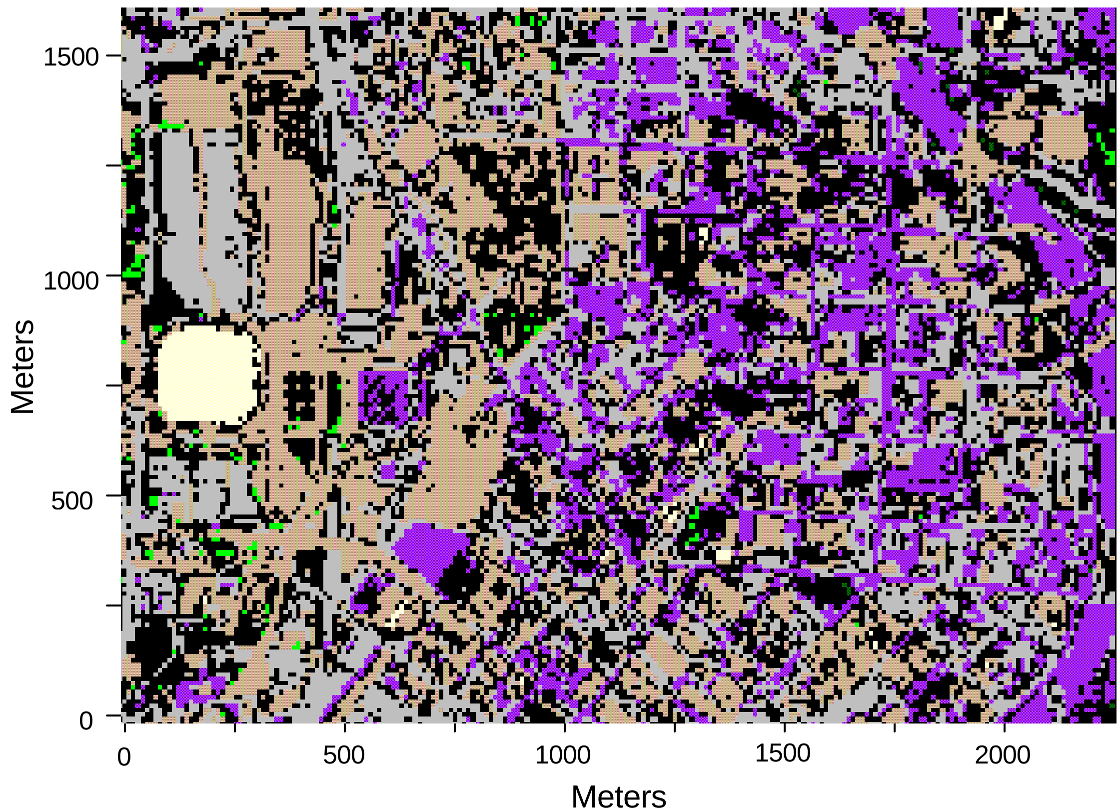
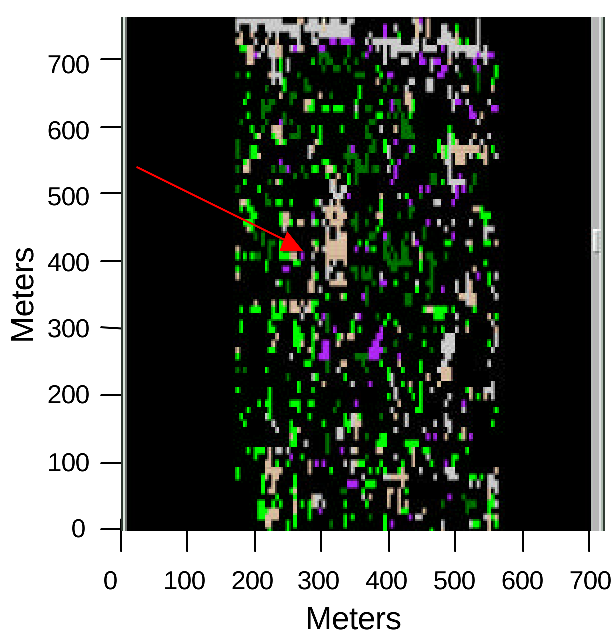
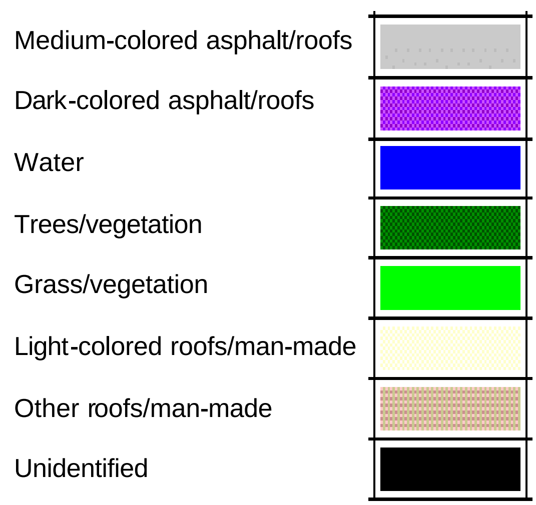


Figure 1. ATLAS data for downtown Atlanta, GA.





This key applies to both Figure 1 and Figure 2

Figure 2. ATLAS data for a typical residential area in Atlanta, GA. A rectangular area from the classification results for Atlanta-residential. In this picture there are approximately 285 single-family homes, 43 multi-family buildings, and 12 unidentified-large buildings. The largest of these is represented by the brown area classified as other roofs/man-made, as indicated by the red arrow. The approximate dimensions of this building are 66 by 122 meters.

composed of a mixture of surfaces including concrete, vegetation, roofs, decks, and pavement. The complexity of the surfaces in a typical pixel in the residential areas creates a spectral curve that cannot be classified using a parallelepiped classification method. (Other classification methods were tried, but the results were similarly inconclusive because of the size of the features of interest and inherent complexity of the pixels.) See **Figure 2** for an example of the classification results over a residential area in Atlanta. Based on the analysis, we conclude that ATLAS data are unsuitable for the task of analyzing the fabric of a city, because its resolution is not high enough to resolve features of interest, especially in residential neighborhoods.

2.2 Black and White Photography

Another possible approach to characterizing the fabric of a region is to combine black-and-white aerial photography with remotely-sensed data, or to use these photographs exclusively. Using high-resolution (about 0.5m, map scale of 1:24,000) aerial photos allow a more accurate estimation of surface makeup in urban areas as well as other regions. These aerial photos are produced from standard black-and-white photographic film that is digitized by scanning the pictures into a computer. These photos are then georeferenced by using existing topographic maps or ground control points. Although these areas can be scanned in at virtually any pixel resolution, the quality of these photographs is limited by the quality of the film, errors inherent in the scanning process, and ultimately by the original map scale. Even with these limitations, areas of the various surfaces in a variety of land-uses and categories could be estimated, and the reflectance of a particular surface could be roughly computed based on the one band of data over the visible range if some ground truthing and data calibration is performed. A georeferenced black-and-white photograph of residential and downtown areas near the Georgia Dome (area shown in Figure 1) that was used to determine the fabric of that urban area is shown in **Figure 3**.

The method used to obtain surface areas from black-and-white digital photos relies on the use of the Imagine software to display the selected images for visualizing a surface of interest. Visual selection is possible because of the photograph's scale (1:24,000) and a 0.5-meter resolution allowing a comfortable discrimination of objects and land-uses/land-covers (LULC). Areas that are relatively clearer and easier to identify are typically roads and roofs. Since roads are continuous over an area they can be selected fairly accurately even when partially obscured by shadows from trees, homes, or covered by other features. The discrimination of roofs is less accurate than that of roads since shadows obscure their edges. Architectural features such as decks, porches, awnings, or elaborate hip and valley roofs of the buildings further complicate the shadow patterns, making it even harder to determine accurately the surface area of a roof. After determining the area of selected roads and roofs, the surface-types of the remaining areas are unclear.

Thus, this method produces general information that is subject to inaccuracy, since it is dependent on visual detection and proper selection of areas that can be blurred by shadows or obscured by other features. In addition, this method is time-consuming, and since it is subjective it has limited reproducibility. However, this method can yield more detailed information on the features in residential areas than the 10-meter-resolution ATLAS data.

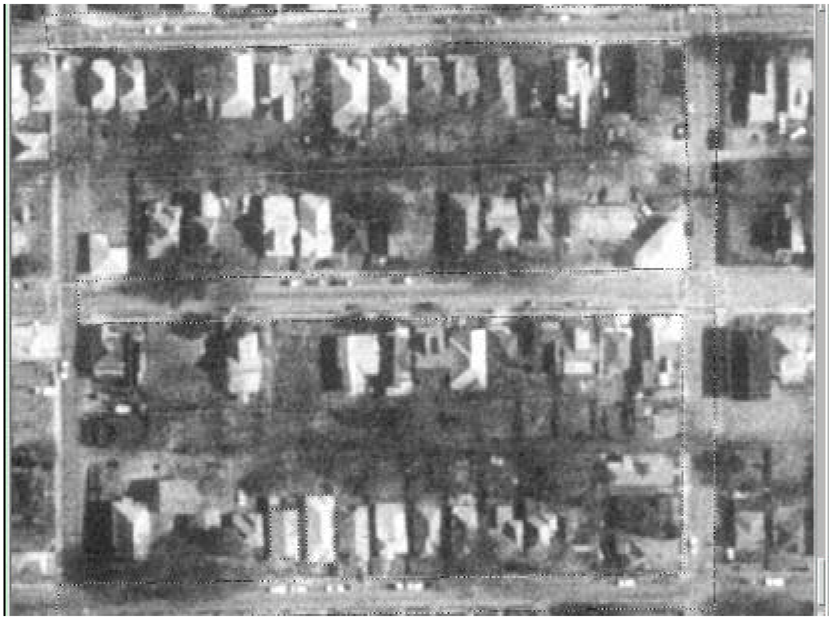


Figure 3. Geo-referenced black-and-white photograph of a residential area near downtown Atlanta, GA. A portion from a geo-referenced black and white photograph of a residential area near downtown Atlanta.

2.3 Color Infrared Photography

Some improvement over the results attained with black-and-white photographs can be achieved by using color infrared photography, also with 0.50-m resolution. By defining user-selected areas using the same method described above, estimates of the areas of various surfaces can be made. Since these photos are produced by adding false colors to one band of data in the infrared (IR) region of the solar spectrum to make the edges of features clearer, the result would be to improve the accuracy of surface-estimation techniques over the use of black-and-white photos. These photos are produced in essentially the same manner as the black-and-white aerial photos. The only difference is that standard film is replaced by IR sensitive film in infrared photography.

Color infrared photos are relatively clearer than black-and-white photographs (see **Figure 4**), although some areas are still obscured by trees and other unknown features, making identification of many surface-types difficult or impossible. Unfortunately, this approach has the same disadvantage of being user-defined and therefore time-consuming and subjective. Therefore, the same limitations exist with this data as with black-and-white photos.

2.4 Custom Color Digital Orthophotos

Of all approaches tested, this approach has the highest potential for accurately producing estimates of surface areas for various land covers and uses in a region. To obtain these custom color high-resolution photos a digital camera is flown aboard a low-altitude aircraft equipped with a GPS (Global Positioning System) and a computer for acquiring and storing data from both the camera and the GPS. The data collected by the GPS system along with topographical data are used in the process of orthorectification. Thus, errors created by the terrain and angle between the camera and surface are minimized.

Using true color aerial photography at a 0.30-m pixel size, it is possible to identify clearly the materials and surfaces that make up the fabric of an area, e.g., **Figure 5**. Using a classification procedure similar to that used with ATLAS data, a semi-automatic procedure for classifying the surfaces of a city can be developed. In a color photograph, the red, green, and blue (RGB) bands data (in the color photos for Sacramento, the red band corresponded to wavelength of 600-700νm, peaking at 650νm; green 500-600νm, peaking at 535νm; and blue 390-500νm, peaking at 440νm) can be used in a parallelepiped classification scheme in the same way the bands of ATLAS data were used. However, all three bands are in the visible spectrum and thus do not cover the entire solar and thermal radiative ranges. For this reason, limited information can be acquired from this data type.

An advantage of custom aerial color photography is that flights can be scheduled as desired. Accordingly, the photos can be taken at solar noon, thus minimizing the inaccuracies introduced by shadows. In addition, the high resolution allows for the calibration of photographs (RGB bands) with laboratory-measured reference panels that can be placed under the flight path in the field. Panels as small as 0.30x0.30m can be detected in the photographs, but larger panels can be used for more reliable calibration. Such laboratory-calibrated reference panels can be used to calibrate the red, green, and blue bands of the photograph, therefore making it possible to

Figure 4. An example of a color-infrared photograph.

Figure 5. An example of a color photograph at 1-foot resolution.

estimate the reflectance of any surface in the photograph over the wavelengths covered by the sensor of the camera. Another method of calibrating the bands of the photograph is to take field albedo measurements of features covered in the photographs, such as roads or roofs.

2.5 Costs of Options

Several of the options explored are commercially available. The black and white orthophotos can be acquired at a cost of approximately $10 per square kilometer, while the color infra-red photographs cost $20 per square kilometer. The cost for each of these data types includes scanning the data into a digital format and orthorectification. These data are available for several major cities in the United States. The cost is low because these aerial photographs were not acquired or scanned on a custom basis and hence, were taken between 1990 and 1997. The custom digital orthophotos acquired for this task cost approximately $150 per square kilometer. If larger areas were acquired (greater than 200 square kilometers), the cost could be reduced to under $80 per square kilometer. The cost for digital orthophotos is lower than traditional aerial photographs because of the reduced materials cost and processing time associated with the use of digital cameras and on-board computer systems (GPS) that collect flight information used in orthorectification. The cost of each data type can vary since they are sold through private companies and prices vary among retailers.

Custom flights typically increase expenses significantly but are often the only viable option when there are no existing data. or existing data are outdated, or unsuitable for a task. The more automated and standardized a procedure is the lower the cost. Thus, the costs associated with a custom flight through a private company with developed methods to expeditiously provide data at a low cost cannot be compared with those incurred through a custom flight developed for scientific purposes. Because of the differences between the organizations producing commercially available products and those producing scientific data, a cost comparison including the ATLAS data would be incongruous.

2.6 Integrating ATLAS and Orthophoto Data

The primary advantage of custom color orthophotos over ATLAS data is their superior resolution. This allows good discrimination of surface-types, e.g., sidewalks, parking lots, streets, grass, trees, roofs, and other features in the urban environment. These orthophotos are also advantageous because even if it is not possible to classify a particular area by its value in the red, green, and blue bands it would still be possible to determine the features of interest visually, since the resolution of the photographs provides a great deal of detail. Therefore, if an automatic classification method is developed, it will be possible to assess its accuracy by visually classifying an area and comparing the results of the visual classification with those of the automatic classification. With ATLAS data alone, an accuracy assessment would be difficult, since fieldwork would be needed for ground truthing.

However, ATLAS has the advantage of providing relatively more continuous coverage in space and radiative spectrum than aerial photographs. The 15 bands of ATLAS in visible, near infrared, and infrared ranges are very useful in characterizing the thermal aspects of various surfaces, which aerial photographs cannot provide. ATLAS data can also yield 10-m integrated albedo and NDVI (normalized difference vegetation index), which is well suited to automation of the process.

Custom photography has the disadvantage of accounting for the reflectance of a material only over the visible wavelengths of light from 0.4 to 1.0µm. For the purpose of this study, the solar spectrum used in albedo calculation ranges from 0.3 to 2.5 µm. ATLAS data cover 0.45 to 12.2 µm. Once these data are corrected for atmospheric conditions and are orthorectified, they can be used to calculate the reflectance and albedo of the identifiable features. Based on these considerations, it appears that the best possible use of these data in characterizing the fabric of a city can be obtained by combining ATLAS information with the detailed data on the composition of an area as provided by orthophotos.

3. Method of Analysis for Custom Color Digital Orthophotos

The color aerial photographs obtained for Sacramento covered a total of about 65 square km (25 square miles). At 0.30-m resolution, approximately $7x10^8$ pixels of data were collected. It was impossible to review all these data visually in detail. Hence, a semi-automated method to classify the data was deemed necessary.

Initially, we analyzed the three bands of RGB data for a selected set of data, searching for characteristic signatures for various surfaces. Unfortunately, since there were significant similarities between the characteristics of various surfaces (such as roofs, pavements, grass, trees) this approach was unsuccessful. We then utilized a special feature available on ERDAS/Imagine software to outline pavements, roofs, and green areas automatically (See Appendix A). Although the results were somewhat promising, the procedure failed to distinguish accurately between driveways, parking lots, and streets, and between grass and trees (See **Figure 6** for an example of such an application). Eventually, we devised a semi-automatic system to sample the data and visually identify the surface-type for each pixel. The method has four steps:

1. Visual inspection of aerial photographs and preparation of a list of various surface-types identifiable in the photos;
2. Grouping of surface categories into major components;
3. Random sampling a subset of data for each region (through a Monte-Carlo sampling approach), and visual inspection of each sample and the assignment of a surface classification to it; and finally
4. Extrapolating the results to the entire Sacramento region, using USGS LULC as a basis.

3.1 Identification of Surface-Types

Each area photographed is visually inspected using the ERDAS/Imagine software. The purpose of this visual exercise is to identify qualitatively all surface-types and land-covers that can be seen at the resolution of the data (in this case, 0.30 m). For Sacramento, the surface-types that were visually identified and used in the analysis are shown in **Table 2**.

Figure 6. An example of using ERDAS software to classify land-use.

Table 2. Visually identifiable features of interest in the Sacramento regions (based on aerial photographs).

Category	Description	Category	Description
1	Unidentified	16	Swimming Pool
2	Tree Covering Roof	17	Auto Covering Road
3	Tree Covering Road	18	Private Paved Surfaces
4	Tree Covering Sidewalk	19	Parking Deck
5	Tree Covering Parking	20	Alley
6	Tree Covering Grass	21	Water
7	Tree Covering Dry/Barren Land	22	Grass on Roof
8	Tree Covering Other	23	Train Tracks
9	Tree Covering Alley	24	Auto Covering Parking
10	Roof	25	Recreational Surface
11	Road	26	Residential Driveway
12	Sidewalk	27	Awning
13	Parking Area	28	Channel Road
14	Grass	29	Channel Land
15	Dry/Barren Land	30	Other Feature (not of interest)

Although more details can be seen in the photos (e.g., mailboxes, small benches, etc.), the categories identified in Table 2 covered most surfaces of interest. In general, the "Other Feature" category was a very small fraction (less than 1%) of the selected random samples. Also, a distinction was made between category 1, "Unidentified", and category 30, "Other Feature": those surfaces classified as "Unidentified" could not be accurately identified; while those in the "Other Feature" category could, but this identification was not relevant to this study. This distinction was necessary to avoid assigning the known features incorrectly.

3.2 Grouping the Surface-Types

The grouping of surface-types is done differently for "above-the-canopy" and "under-the-canopy" categories. The criteria for grouping above-the-canopy categories was primarily based on requirements for meteorological modeling. However, the under-the-canopy categories were grouped based on requirements for implementation of heat-island reduction measures; the under-the-canopy categories show the actual and functional land-use categories as they are built. Hence, there is a difference in the definition of the categories for above-the-canopy and under-the-canopy under the same category type.

3.2.1 Above-the-canopy grouping

The grouping is summarized in **Table 3**. This was done in order to aggregate similar materials that may also have similar characteristics.

Roof include "Roof" (Cat. 10) and "Awning" (Cat. 27).

Road includes "Road" (Cat. 11) and "Channel Road" (Cat. 28).

Parking Area includes "Parking Area" (Cat. 13) and "Parking Deck" (Cat. 19).

Sidewalk & Driveway includes "Sidewalk" (Cat. 12) and "Residential Driveway" (Cat. 26).

Tree Cover includes various tree categories (Cat. 2-9).

Grass includes "Grass" (Cat. 14) and "Grass on Roof" (Cat. 22).

Barren Land includes "Dry/Barren Land" (Cat. 15), and "Channel Land" (Cat. 29).

Miscellaneous includes "Swimming Pool" (Cat. 16), "Auto Covering Road" (Cat. 17), "Private Paved Surfaces" (Cat. 18), "Alley" (Cat. 20), "Water" (Cat. 21), "Train Tracks" (Cat. 23), "Auto Covering Parking" (Cat. 24), "Recreational Surface" (Cat. 25), and "Other Feature" (Cat. 30).

3.2.2 Under-the-canopy grouping

The grouping is also summarized in Table 3. For characterization of the surfaces under the canopy, the primarily criteria for grouping was the function or use of the surface-type. For implementation purposes, one would like to "see" what lies beneath the canopy of trees. Hence, in order to calculate areas of various surfaces under the canopy, the areas beneath the trees are totaled. In these calculations it is assumed that the areas occupied by tree trunks are negligible. Also, a "Private Paved Surfaces" category was added to distinguish between those surfaces owned privately and those owned publicly. Obviously, this grouping can be rearranged depending on specific needs.

Roof includes "Tree Covering Roof" (Cat. 2), "Roof" (Cat. 10), "Parking Deck" (Cat. 19), "Grass on Roof" (Cat. 22), and "Awning" (Cat. 27).

Road includes "Tree Covering Road" (Cat. 3), "Tree Covering Alley" (Cat. 9), "Road" (Cat. 11), "Auto Covering Road" (Cat. 17), "Alley" (Cat. 20), and "Channel Road" (Cat. 28).

Parking Area includes "Tree Covering Parking" (Cat. 5), "Parking Area" (Cat. 13), and "Auto Covering Parking" (Cat. 24).

Sidewalk includes "Tree Covering Sidewalk" (Cat. 4) and "Sidewalk" (Cat. 12).

Private Paved Surfaces includes "Private Paved Surfaces" (Cat. 18) and "Residential Driveway" (Cat. 26).

Grass includes "Tree Covering Grass" (Cat. 6) and "Grass" (Cat. 14).

Barren Land includes "Tree Covering Dry/Barren Land" (Cat. 7), "Dry/Barren Land" (Cat. 15), and "Channel Land" (Cat. 29).

Miscellaneous includes "Tree Covering Other" (Cat. 8), "Swimming Pool" (Cat. 16), "Water" (Cat. 21), "Train Tracks" (Cat. 23), "Recreational Surface" (Cat. 25), and "Other Feature" (Cat. 30).

Table 3. Major surface-types

Surface-Type	Categories included*	Surface-Type	Categories included
Above-the-canopy view			
Roof	10, 27	Tree Cover	2-9
Road	11, 28	Grass	6, 14
Parking Area	13, 19	Barren Land	15, 29
Sidewalk & Driveway	12, 26	Miscellaneous	16-18, 20, 21, 23-25, 30
Under-the-canopy view			
Roof	2, 10, 19, 22, 27	Private Paved Surfaces	18, 26
Road	3, 9, 11, 17, 20, 28	Grass	6, 14
Parking Area	5, 13, 24	Barren Land	7, 15, 29
Sidewalk	4, 12	Miscellaneous	8, 16, 21, 23, 25, 30

* Surface-type categories are defined in Table 2.

3.3 Identification of Random Samples

Once the surface-types have been identified, as in Table 2, the next task is to determine the fractional areas covered by each type respectively. We used the Monte-Carlo statistical technique for this propose. The method is a simple process of randomly selecting pixels and visually identifying their surface-types and their percentages. The results are summarized as percentages for various surfaces. Initially, when the number of sample points is small, there is a large fluctuation in the percentage of various surface areas. As the number of sample points increases, these fluctuations become smaller and approach asymptotic values. The process is stopped when the fluctuations in the percentages of each and all surface-types is less than an acceptable value (here less than 1%). Experimental analysis of the approach indicated that a random sample size of 400-600 points/pixels was sufficient to accurately identify the fabric of an area of about 5-10 square kilometers ($1x10^4$ to $2x10^4$ pixels).

To locate the sample points randomly in a given region, Imagine’s capability to generate random numbers was used. A random-number generator was used to create some 400-600 points for each scene (this is the range of points at which the fluctuations in the area percentages stabilizes). A scene in this case averaged 5,025,240m^2 in area. Note that the scene area and number of sample points should be selected in a coordinated fashion so that a reasonable distribution of random points is achieved. That is, the scene area should be selected so that a large number of surfaces are included and so that the randomly selected points are distributed at reasonable density.

Once these points have been generated, they are recalled, and each is visually inspected and assigned to one of the surface-types listed in Table 2. Given the fine resolution of these images, one can almost always identify the surface-type. Even areas in the shade (recall that the flights were scheduled around solar noon for minimum shadows) can be relatively easily identified from continuity and context. Those surfaces that are impossible to identify are entered in the "Unidentified" category.

In the Monte-Carlo approach, as the sample size is increased the standard errors of the estimates of percentages for each land cover area are expected to decrease. We performed a statistical exercise to evaluate the impact of the sample size on standard error of estimate. In this exercise, we calculated the standard deviation of the observations progressively for all observations (samples 1-400), the last 300 observations (samples 101-400), the last 200 observations (samples 201-400), and the last 100 observations (samples 301-400). **Table 4** shows the results of this analysis for both above and under the canopy for downtown Sacramento. It can be clearly observed that the standard deviations get progressively smaller as the sample size is increased, indicating convergence towards the population means. Based on this analysis, the estimated 95% confidence interval is less than 10% of the percentage for almost all surface-types.

3.4 Extrapolation of Data for Climate Simulation

For meteorological and air-quality modeling, the characteristics of the surface in different regions must be investigated. Because of the difficulty of carrying out the thorough measurement of the entire area (modeling domain), it is necessary to extrapolate the small-scale data to region of interest.

We used the Land-Use/Land-Cover (LULC) data from the United States Geological Survey (USGS) to extrapolate the limited data obtained from the analysis of aerial photos to the entire Sacramento area. LULC data classify the surface at 200-meter resolution, into many different urban and non-urban categories. The LULC classification for urban areas includes: residential, commercial/service, industrial, transportation/communications, industrial/commercial, mixed urban or built-up land, and other mixed urban and build-up land. The following steps were taken in order to extrapolate the data from aerial photographs to Sacramento region:

1. We first grouped aerial photographs into LULC categories (i.e., residential, commercial/services, industrial, etc).
2. We then calculated the average characteristics (fabric) for each category.
3. We assigned the observed land-use categories (OLUC) from the analysis of the aerial photographs to those of the LULC data set. For instance, for a residential LULC category, we assigned the percentage areas obtained from aerial photos.

Table 4. The impact of sample size on estimates of area percentages of land-use categories for downtown Sacramento. The entries show the "sample mean" in percentage of areas; the numbers in parenthesis are standard deviations of the means. Note that the above-the-canopy percentages show the "bird's-eye" view of the surfaces; under-the-canopy percentages are the actual land-use types.

	Above the Canopy				Under the Canopy			
Sample Size Surface Type	1-400	101-400	201-400	301-400	1-400	101-400	201-400	301-400
Roof	22.75 (3.64)	21.81 (1.43)	21.35 (0.93)	21.97 (0.32)	26.40 (4.11)	25.48 (1.74)	24.60 (0.75)	24.99 (0.26)
Road	20.77 (5.10)	22.65 (1.06)	23.13 (0.53)	23.01 (0.64)	28.16 (5.47)	30.25 (1.09)	30.68 (0.64)	30.29 (0.58)
Parking Area	15.48 (5.46)	13.60 (0.56)	12.65 (0.31)	11.58 (0.33)	12.82 (5.87)	11.22 (1.22)	10.64 (0.99)	9.80 (0.21)
Sidewalk	6.52 (5.66)	5.48 (0.56)	5.23 (0.31)	5.32 (0.33)	9.73 (5.38)	8.91 (0.48)	9.09 (0.44)	9.31 (0.45)
Grass	5.80 (1.72)	6.02 (1.29)	6.75 (0.70)	7.27 (0.18)	9.86 (2.19)	10.46 (1.75)	11.45 (1.04)	12.20 (0.27)
Barren Land	2.10 (1.16)	2.73 (0.37)	2.89 (0.18)	2.76 (0.11)	3.14 (1.01)	3.59 (0.33)	3.68 (0.20)	3.53 (0.12)
Tree Cover	19.24 (3.95)	21.00 (1.07)	21.47 (0.64)	21.57 (0.38)				
Private Surfaces					0.63 (0.56)	0.46 (0.19)	0.35 (0.07)	0.29 (0.02)

4. Finally, the 200-meter resolution data were averaged to obtain data at 2000-meter resolution used in meteorological and air-quality modeling.

4. Results from Sacramento, CA

In this section, some specific results are reviewed based on the data we acquired from the Sacramento flights. Two flights were performed on sunny, cloud-free and clear days, around solar noon to minimize the impact of shadows (August 20, September 7, and November 4, 1998). On all days, the specially-equipped aircraft took off from Sacramento Executive Airport and flew at approximately 1.5km (5000ft) over selected areas. These flights covered a total of about 65 square km (25 square miles). All data were taken at 0.30-m resolution. For the first flight, 14 different areas were selected to cover a broad spectrum of land uses in Sacramento, as well as different neighborhood ages (recent vs. old) and densities (e.g., high vs. low-density built-up areas).

Several colored and black-and-white panels were placed on the ground (under the flight path) to calibrate the remotely sensed data. The panels were distributed on various backgrounds, i.e., on 1) the roof of a tall building (the white-roofed SMUD Headquarters building), 2) a grass area, and 3) an asphalt driveway (See **Figures 7 and 8**). The purpose of this exercise was primarily to estimate the albedo of the surfaces in each of the scenes. Another objective was to determine the change (if any) of measured reflectivity of the panels (as observed from the aircraft) as a function of background color and type, and also to study the edge effect that appears around the panels and other objects in the photograph.

Since the Sacramento metropolitan area is predominantly covered by residential areas, an accurate assessment of the range and coverage of different surfaces in residential neighborhoods was necessary. Therefore, eight residential areas varying in age, density, and level of vegetation were analyzed. Additionally, an office area, two industrial and and two commercial areas were selected in order to cover the typical land-uses in the Sacramento area. Downtown Sacramento, consisting of office buildings, shops, and residential buildings, was also studied. These areas are described below.

4.1 Downtown Sacramento and City Center (predominantly office buildings with some residences)

Downtown Sacramento was defined as a stand-alone land use. **Figure 9** shows the actual portion of the aerial photograph that was analyzed in this task. The visible portion of this photo is $4.73km^2$ in area and appears to contain predominantly multi-storied office buildings with some residential land use scattered in between (these can be seen, for example, in the southern and northeastern portions of the photograph). The State Capitol is clearly seen in the center of this photo. This area is one of the older zones in Sacramento and has relatively high vegetative cover compared to newer suburban areas.

The random number generator, mentioned earlier, was used to generate x- and y-coordinates for 400 points and to overlay them on this photo. **Figure 10** shows the estimated fraction of various surface-types as the number of samples is increased. It can be seen that when the number of samples is small there is a large fluctuation in the estimated percentages for various surfaces. As the sample size grows, e.g., the number of points or counts increases, the fluctuation is dampened and the percentages stabilize. In this figure, it appears that there is a relative stability beginning at a total count of around 30. **Table 5** (row 1) summarizes the results from an above-the-canopy perspective for this area.

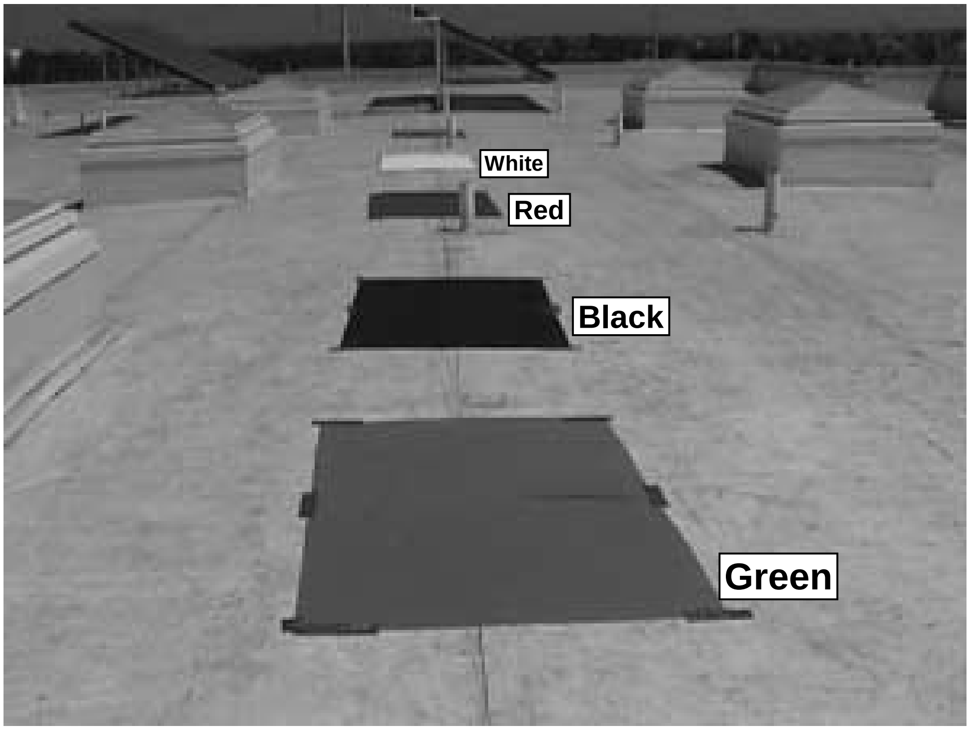


Figure 7. Calibration panels on the roof of the SMUD building.

Figure 8. Calibration panels in the parking area of the SMUD building.

Figure 9. Aerial photo of downtown Sacramento.

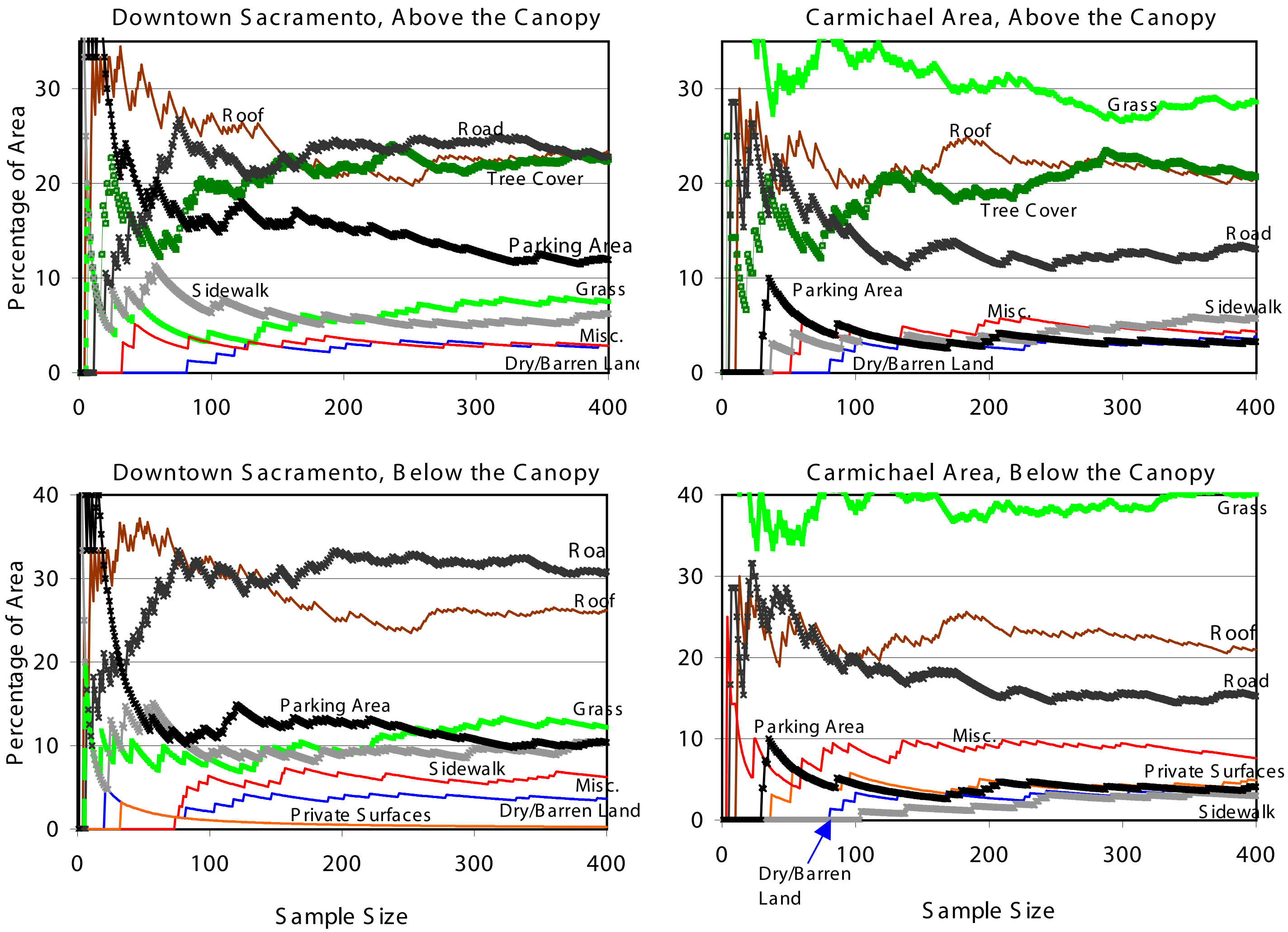


Figure 10. Percentage of surface types for two areas above and below the canopy with increasing sample size. Note that the fluctuations in percentage of areas dampen as the sample size increases.

Table 5. Above-the-canopy view of Sacramento, CA. Entries are rounded to nearest 0.5. Numbers in parenthesis show the standard deviations of the last 100 samples.

Area	Surface-type (percent of total cover) Roof	Road	Parking Area	Side-walk	Tree Cover	Grass	Barren Land	Misc.
1. Downtown Sacramento	23.0 (0.32)	23.0 (0.64)	12.0 (0.33)	6.0 (0.28)	22.5 (0.38)	7.5 (0.18)	3.0 (0.11)	3.0
2. Industrial Areas								
a) Richards Boulevard Are	23.5 (0.51)	7.5 (0.18)	20.0 (0.90)	1.5 (0.08)	8.0 (0.19)	6.0 (0.25)	19.5 (0.69)	14.5
b) Port of Sacramento Are	19.0 (0.36)	10.5 (0.20)	32.0 (0.44)	1.5 (0.15)	3.0 (0.21)	5.5 (0.16)	15.5 (0.27)	13.0
3. Typical Office Area								
a) Sacramento County Branch Center Are	16.0 (0.44)	12.0 (0.20)	33.5 (0.49)	3.0 (0.18)	4.5 (0.20)	16.5 (0.62)	10.5 (0.31)	3.5
4. Typical Commercial Areas								
a) Florin Shopping Center Are	19.0 (0.30)	11.5 (0.44)	54.0 (0.64)	2.0 (0.10)	3.0 (0.13)	2.0 (0.10)	6.5 (0.19)	2.0
b) California Exposition Are	20.5 (0.53)	16.0 (0.28)	25.0 (0.38)	3.5 (0.18)	8.0 (0.15)	11.5 (0.20)	9.5 (0.23)	6.5
5. Typical Residential Areas								
a) Pocket Road Are	25.0 (0.28)	14.5 (0.31)	1.5 (0.07)	12.5 (0.29)	12.0 (0.33)	25.5 (0.29)	3.5 (0.11)	5.0
b) Jack Davis Park Are	19.5 (0.85)	13.0 (0.39)	2.0 (0.19)	8.5 (0.18)	14.5 (0.37)	27.5 (0.54)	11.0 (0.31)	4.0
c) Hagginwood Park Are	11.5 (0.31)	15.5 (0.51)	5.0 (0.21)	5.5 (0.16)	11.0 (0.19)	23.5 (0.42)	21.5 (0.66)	6.5
d) Elk Grove Are	16.5 (0.19)	11.0 (0.31)	1.0 (0.09)	9.0 (0.62)	1.5 (0.14)	31.0 (0.32)	19.5 (0.32)	10.0
e) Del Paso Are	22.0 (0.72)	11.0 (0.29)	18.5 (0.76)	5.0 (0.23)	20.0 (0.17)	13.5 (0.20)	4.5 (0.26)	6.0
f) Tahoe Park Are	20.5 (0.86)	10.5 (0.53)	2.5 (0.11)	10.0 (0.23)	23.5 (0.66)	22.0 (0.29)	8.0 (0.21)	3.0
g) East Downtown Are	23.5 (0.36)	17.5 (0.27)	9.5 (0.28)	4.5 (0.17)	27.0 (0.45)	7.0 (0.41)	2.0 (0.15)	8.5
h) Carmichael Are	20.5 (0.60)	13.0 (0.37)	3.5 (0.14)	5.5 (0.17)	20.5 (0.23)	28.5 (0.70)	4.0 (0.24)	4.5

As shown in this table, the surface-types "Roof", "Road", and "Tree Cover" are all present in nearly equal percentages. This type of classification is suitable for meteorological and air-quality modeling, where vegetative canopies are "seen" from above by the models. However, for implementation of heat-island reduction measures an "under-the-canopy" view is more appropriate. In this case, trees reduce to mere trunks (i.e. under the crowns), and thus the percentages of the areas covered by trees become negligible (actually around 0.2% or less). A warning is appropriate here: the results in this table do not necessarily apply to other cities' downtown areas. Sacramento is forested to a relatively high degree (in the center) and the size and distribution of buildings seen in this photo are not typical of other American cities. The above-the-canopy data shows that approximately 30% of the area in the city center of Sacramento is vegetated (trees and grass), while under-the-canopy data show that about 79% is covered by man-made materials (roofs, roads, sidewalks, parking areas, and private surfaces).

Table 6 (row 1), is a recast of the data from an under-the-canopy point of view. As indicated in Tables 5 and 6, in downtown Sacramento trees cover a high percentage of the surfaces. In fact, approximately 28% of the road area, 67% of the sidewalks, and almost all of the area identified as miscellaneous is covered by trees. Most of the area under the tree canopy is covered by man-made surfaces, with the exception of the "Grass" category, consisting of primarily the South Side and Capitol Parks, and the mall area and the "Barren Land" category. The "Barren Land" category comprises only 3.5% of the downtown area and consists of a vacant lot, construction site, and some small patches of dry soil. Accordingly, practically all of the land in this downtown area is developed.

4.2 Typical Industrial Areas

Two main industrial areas were identified for surface-type classification. The first, the Richards Boulevard area, is notable for its large areas primarily used for transportation. There are many train tracks and large parking lots for trucking operations. There are also some office buildings and industrial equipment. The other area, covering the Port of Sacramento and the surrounding land used for industrial purposes, is also used heavily for transportation. In this area there are many office buildings along with some industrial equipment and outdoor supply storage.

4.2.1 Richards Boulevard Area

The Richard Boulevard area (**Figure 11**) is just north of the downtown Sacramento area discussed above in section 4.1. The visible portion of this photo is 2.3km^2 in area. As in the previous case, the random-number generator was used to generate x- and y-coordinates for 400 points and to overlay them on this photo. The same process mentioned earlier, assigning the categories, is repeated again in this instance.

The results of the Monte-Carlo approach to characterize the surface-type distribution show that the above-the-canopy makeup of this area is about 23% roofs; 29% roads, parking areas, and sidewalks; 14% trees and grass; and 34% others (see Table 5: row 2a). Table 6 (row 2a), a recast of the data from an under-the-canopy view, shows that trees mostly shade parking areas and grass. For this industrial area of Sacramento, 7% of parking areas are covered by trees. Roofs

Table 6. Under-the-canopy view of Sacramento, CA. Entries are rounded to nearest 0.5. Numbers in parenthesis show the standard deviations of the last 100 samples.

Area	Surface-type (percent of total cover) Roof	Road	Parking Area	Sidewalk/ Driveway	Private Surfaces	Grass	Barren Land	Misc.
1. Downtown Sacramento	26.0 (0.26)	31.0 (0.58)	10.5 (0.21)	10.5 (0.45)	0.5 (0.02)	12.0 (0.27)	3.5 (0.12)	6.0
2. Industrial Areas								
a) Richards Boulevard Area	23.5 (0.51)	7.5 (0.18)	22.5 (0.82)	1.5 (0.10)	3.5 (0.30)	9.5 (0.29)	22.0 (0.59)	10.5
b) Port of Sacramento Area	19.0 (0.36)	10.5 (0.19)	34.0 (0.45)	1.5 (0.13)	5.0 (0.20)	6.0 (0.17)	17.5 (0.19)	6.5
3. Typical Office Area								
a) Sacramento County Branch Center Area	16.0 (0.44)	12.0 (0.20)	36.0 (0.40)	3.0 (0.25)	1.5 (0.11)	18.5 (0.22)	11.0 (0.28)	2.0
4. Typical Commercial Areas								
a) Florin Shopping Center Area	19.0 (0.30)	11.5 (0.44)	56.5 (0.63)	2.0 (0.10)	1.0 (0.10)	2.0 (0.07)	6.5 (0.21)	1.5
b) California Exposition Area	21.0 (0.49)	17.0 (0.34)	27.0 (0.61)	3.5 (0.20)	2.5 (0.17)	16.0 (0.21)	9.5 (0.24)	3.5
5. Typical Residential Areas								
a) Pocket Road Area	25.0 (0.28)	15.0 (0.33)	2.0 (0.08)	7.0 (0.18)	9.0 (0.21)	35.0 (0.40)	3.5 (0.11)	4.0
b) Jack Davis Park Area	19.5 (0.85)	14.5 (0.58)	3.0 (0.17)	6.5 (0.15)	3.0 (0.18)	34.0 (0.79)	13.0 (0.30)	6.5
c) Hagginwood Park Area	11.5 (0.31)	16.5 (0.48)	6.0 (0.24)	5.0 (0.13)	4.0 (0.43)	28.0 (0.38)	24.0 (0.69)	5.0
d) Elk Grove Area	16.5 (0.19)	11.0 (0.33)	1.0 (0.09)	5.0 (0.34)	9.0 (0.35)	32.5 (0.20)	19.5 (0.31)	5.0
e) Del Paso Area	23.0 (0.62)	11.5 (0.27)	22.0 (0.68)	5.0 (0.31)	4.0 (0.31)	25.0 (0.57)	5.0 (0.33)	4.0
f) Tahoe Park Area	21.5 (0.87)	12.0 (0.52)	2.5 (0.13)	6.5 (0.15)	6.0 (0.66)	35.0 (0.30)	9.0 (0.27)	6.5
g) East Downtown Area	28.0 (0.51)	27.0 (0.33)	7.5 (0.24)	7.0 (0.28)	4.5 (0.30)	9.5 (0.34)	2.5 (0.09)	14.0
h) Carmichael Area	21.0 (0.56)	15.5 (0.42)	4.0 (0.10)	3.0 (0.32)	5.0 (0.16)	40.0 (0.61)	4.0 (0.23)	7.5

Figure 11. Aerial photo of Richards Boulevard Area, Sacramento.

and roads are unshaded, but other surface-types, such as grass and barren land, are covered by smaller areas of trees. This area is almost completely developed, although the percentage of "Barren Land" suggests otherwise. Most of the points in the classification that were categorized as barren land appear to be used for transportation and loading of goods onto trains or trucks. The relatively high percentage of "Miscellaneous" surfaces is due to the coverage of the train tracks in this area. In fact, if the category "Train Tracks" were a surface-type, separate from that of "Miscellaneous," it would cover 8.5% of the total area.

4.2.2 Port of Sacramento Area

There is another industrial area near downtown Sacramento. This area covers the Port of Sacramento and surrounding industrial area west of the city center. Along with the port, there are many office buildings and machinery/equipment in this area. **Figure 12** shows the actual part of the orthophoto that was analyzed (again with a mask covering irrelevant land-uses). The visible portion of this photo is $1.9km^2$ in area. The makeup of this industrial area from above the canopy is about 19% roofs; 34% roads, parking areas, and sidewalks; 8% trees and grass; and 29% others. A recast of the data from an under-the-canopy view (Table 5: row 2b) shows that the trees exclusively shade grass, parking areas, and barren land.

As in the Richards Boulevard area, the "Barren Land" percentage suggests that much of the area is undeveloped. This is not the case, however, since it appears that the barren land in and around the Port of Sacramento area is used for transportation and storage of materials. Thus, this area is almost completely developed. The only surface-type with any significant tree cover is "Barren Land," 10% of which is covered by trees. Most of the surface-types in this area have percentages similar to those in the Richards Boulevard area, although the percentage of "Parking Areas" is 60% higher in this area, covering an additional 12% of the total surface. The "Miscellaneous" surface-type here consists mainly of the category "Other Features." In this area, the "Other Features" were typically industrial equipment and supplies.

4.3 Sacramento County Branch Center Area (A Typical Office Area)

In the metropolitan Sacramento area, most of the office areas are interspersed within other land-uses such as the industrial and downtown areas discussed above. They can also be found in residential and commercial land-uses. For this study, one office area was selected. This particular area contrasted starkly with its surroundings: it is homogeneous and its borders are clearly defined by a residential neighborhood, industrial land-use areas, and barren land.

The Sacramento County Branch Center Area (**Figure 13**) is about 13km (8 miles) east of downtown Sacramento along the edge of the residential development in metropolitan Sacramento. It extends from the area designated as the Sacramento County Branch Center along the nearby streets and covers $0.9km^2$. The result of the surface-type analysis above the canopy shows 16% roofs; 48% roads, parking areas, and sidewalk; 9% trees and grass; and 28% others (Table 5: row 3a). A recast of the data from an under-the-canopy point of view shows that trees mainly shade parking areas and grass.

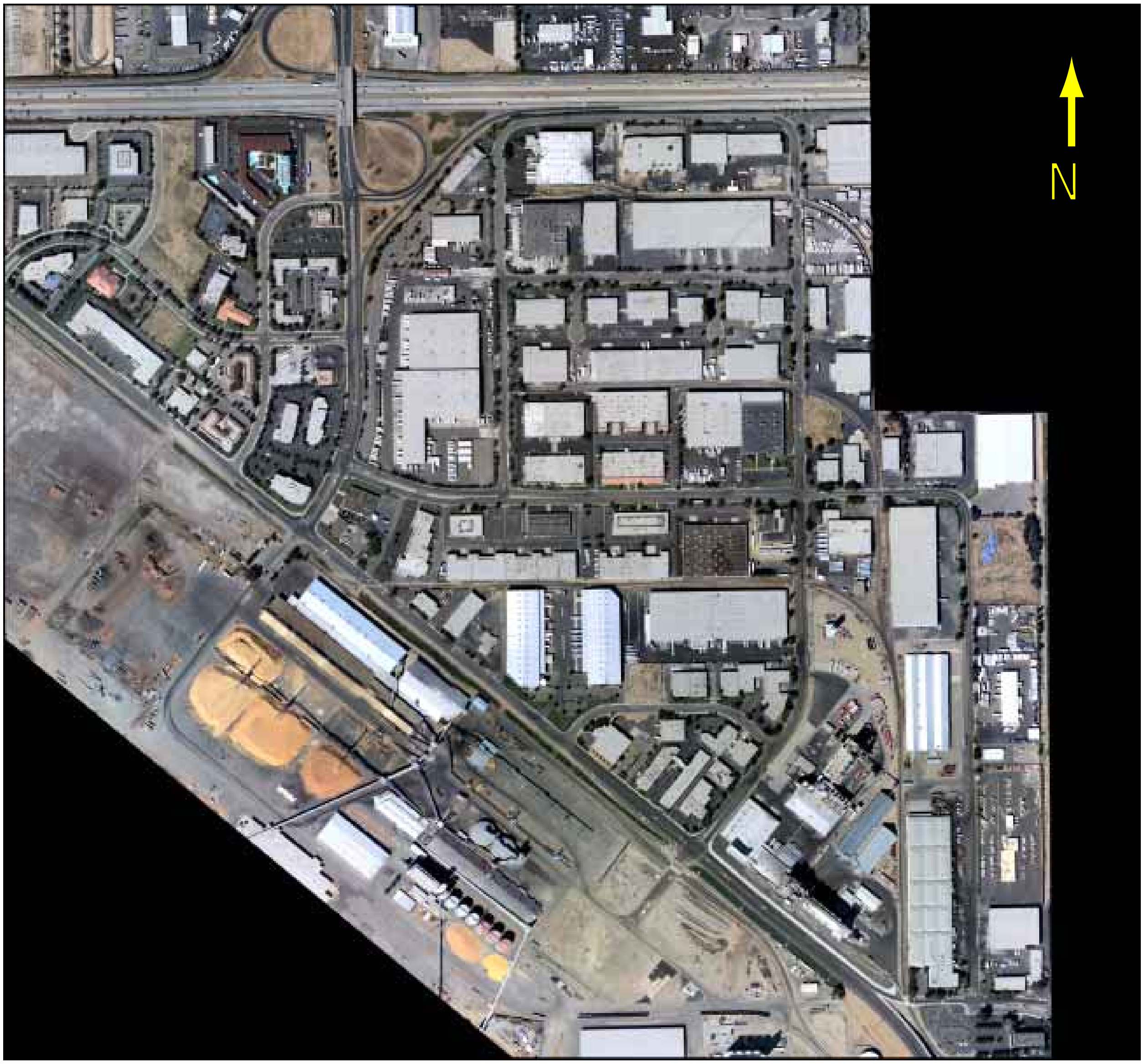


Figure 12. Aerial photo of Port of Sacramento Area.

Figure 13. Aerial photo of Sacramento County Branch Center Area (a typical office area).

As shown above, the primary surface-type is "Parking Area" covering 36% of the area. In fact, more of the area is covered by parking than all of the other man-made surfaces combined. This area is not completely developed, however, and there are a few vacant lots that remain barren. There are also many large grassy lawns making up 18.5% of this area. Although there are trees scattered throughout, they are small and only cover a small portion of the total area.

4.4 Typical Commercial Areas

Within the commercial areas there are a variety of buildings serving as malls, shops, stores, and related services (restaurants, fast-food services, etc). For this analysis, two representative commercial areas were selected. The first, the Florin Shopping Center area, has two large strip malls along with a variety of other buildings, including offices and apartments. The other area, the California Exposition area, has one large shopping mall and several apartment buildings along with offices and other types of buildings customary in commercial areas.

4.4.1 Florin Shopping Center Area

Figure 14 shows the Florin Shopping Center area used in this analysis (unwanted areas are masked). This is primarily a shopping area about 10km (6 miles) southeast of downtown in the Florin community. The area chosen for surface characterization covers 0.6km^2. As in the previous surface-type discussions, Tables 5 and 6 (row 4a) summarize the above- and under-canopy distributions.

As shown above, there is very little tree cover or grass in this area. Most notably, parking areas cover over 50% of the area. This is in dramatic contrast to the total percentage of all vegetated surfaces: only 5% from above the canopy. Most of the trees are sparsely scattered in parking lots, but the percentage of parking areas covered by trees is still only about 3%.

4.4.2 California Exposition Area

This area is a commercial area just north of the California Exposition (**Figure 15**). The area of the selection analyzed is 2.8km^2. As mentioned in the previous surface-type discussions, row 4b of Tables 5 and 6 summarize the above- and under-canopy distributions.

The higher levels of vegetation are because of the fact that this area is less developed than the previous one as indicated by the higher percentage of "Barren Land." The development in this area is also more mixed, with other land-uses than the Florin Shopping Center area. There are several apartment buildings, grassy lawns, and a recreational field. Hence, there are higher percentages of "Grass" and "Tree Cover" in this area. The trees in this area are clearly denser than those in the other commercial area. The surface-type with most of the tree coverage is "Grass," 28% of which is covered by trees.

4.5 Typical Residential Areas

Since residential areas dominate in most of Sacramento, eight different neighborhoods were selected for surface characterization. Inside the Sacramento city limits, 55% of the land is zoned for residential use. In the outlying suburbs, the developed land is predominantly used for

Figure 14. Aerial photo of Florin Shopping Center Area.

Figure 15. Aerial photo of California Exposition Area.

single-family homes rather than commercial, industrial, or offices.

The residential areas differed in amount of vegetation, density, homogeneity of use, and size of housing units. The newest area analyzed was in the Elk Grove community south of Sacramento. Some older established neighborhoods, such as the one in the Carmichael area and those in and near downtown, i.e. Jack Davis Park, were also included in the analysis. Several medium-density areas were analyzed, such as those in the Hagginwood Park and in the Pocket Road areas. In addition, a residential area that was mixed with other land-uses, the Kaiser area, was included.

4.5.1 Pocket Road Area (a 20-year-old single-family residential neighborhood)

The Pocket Road Area consists of 20-year-old, high-density, detached, single-family homes, with moderate-to-low vegetative cover. This area is southwest of downtown Sacramento and is skirted by the Sacramento River. **Figure 16** shows the area actually analyzed in this task. The visible portion of this photo covers $3.26km^2$. It is seen to contain a canal, not quite typical of residential areas but not unusual in Sacramento.

The above- and under-canopy results are presented for this area in row 5a of Tables 5 and 6. The data show that, in this neighborhood, trees do not cover roofs. In this particular residential area, the trees are dispersed throughout the community, and although there are trees around the houses they are not directly next to the buildings. Therefore, as the data show, most of the trees in this area cover grass. In addition, the trees are not large. Other features in this area include parks and schools. As indicated by the low percentage of "Barren Land," all of the land in this neighborhood is developed.

4.5.2 Jack Davis Park Area (An established neighborhood)

This residential area also consists mainly of detached, single-family homes. This area is southeast of downtown Sacramento. In addition to residential homes, it contains a few office buildings, a small park (Jack Davis Park), and a school. **Figure 17** shows the area actually analyzed in this task. The visible portion of this photo covers $0.8km^2$.

The above- and under-canopy results are presented for this area in row 5b of Tables 5 and 6. In its surface-type percentages this area is similar in many ways to the Pocket Road Area. The surface-type percentage that is different from the Pocket Road Area is "Barren Land." This appears to be because grass is not always maintained around the lots of the buildings in this area, and there are even some unpaved areas (bare soil) used for transportation.

4.5.3 Hagginwood Park Area (An established neighborhood with schools and parks)

The Hagginwood Park Area analyzed in this task consists primarily of detached, single-family homes. This area is northeast of downtown Sacramento. It is typical of many residential neighborhoods, containing schools and parks. **Figure 18** shows the area actually analyzed in this task. The visible portion of this photo covers $2.2km^2$.

Figure 16. Aerial photo of Pocket Road Area.

Figure 17. Aerial photo of Jack Davis Park Area.

Figure 18. Aerial photo of Hagginwood Park Area.

The above- and under-canopy results are presented for this area in row 5c of Tables 5 and 6. This area is less developed than the other residential areas analyzed as demonstrated by its percentages of "Barren Land" and "Roof". The high percentage of "Barren Land" can be attributed to the vacant lots throughout the scene and also to some barren land in and around some schools and parks in the area. Consequently, the percentage of "Roof" in this area is low compared to the other residential areas.

4.5.4 Elk Grove Area (A new development)

This area is a new development in the suburbs south of Sacramento in the Elk Grove community. It contains large single-family homes with similar lots and home sizes. Trees are planted throughout the development and there is a large grassy area in its center. **Figure 19** shows the area analyzed in this task. The visible portion of this photo covers $1.5km^2$.

The above- and under-canopy results are presented for this area in row 5d of Tables 5 and 6. The extremely low percentages of "Tree Cover" and "Parking Area" in this area are striking. Although there are trees throughout this development, they cover a relatively small percentage of the area since they are young and quite small. The percentage of "Parking Area" is low because there are no schools, parks, or non-residential buildings in this area that require parking lots. The percentage of "Barren Land" is also relatively high in this area. From the picture (**Figure 20**), however, it appears that this land will be developed in the future: it is laid out in plots similar to the existing development.

4.5.5 Del Paso Area (A mixed residential/commercial neighborhood)

The Del Paso Area is a mixed residential area northeast of downtown in the Del Paso community. In addition to single-family detached homes, this area contains a hospital, office buildings, shops, parks, schools, and apartments. **Figure 21** shows the area of $0.2km^2$ that was analyzed in this task.

The above- and under-canopy results are presented for this area in row 5e of Tables 5 and 6. The many land-uses in this area are reflected in the surface-type percentages of the Del Paso Area. Primarily, the percentage of "Parking Area" is higher in this area than in any of the other residential areas. Hence, the percentage of "Grass" is relatively low. However, even with the shrinking of the grassy area, the "Tree Cover" surface area remains high due to the many mature trees in the parks and around the residential homes and apartments. It is interesting to note that trees covered about half of the grassy areas in this scene.

4.5.6 Tahoe Park Area (An established neighborhood with park areas and schools)

This area is on the south side of highway 50 near the Sacramento Municipal Utilities District building southeast of downtown. It consists mainly of single-family detached homes. There are also several parks and schools in this area. **Figure 22** shows the area actually analyzed in this task. The visible portion of this photo is $2.7km^2$.

Figure 19. Aerial photo of the residential portion of Elk Grove area.

Figure 20. Aerial photo of larger Elk Grove Area.

Figure 21. Aerial photo of Del Paso Area.

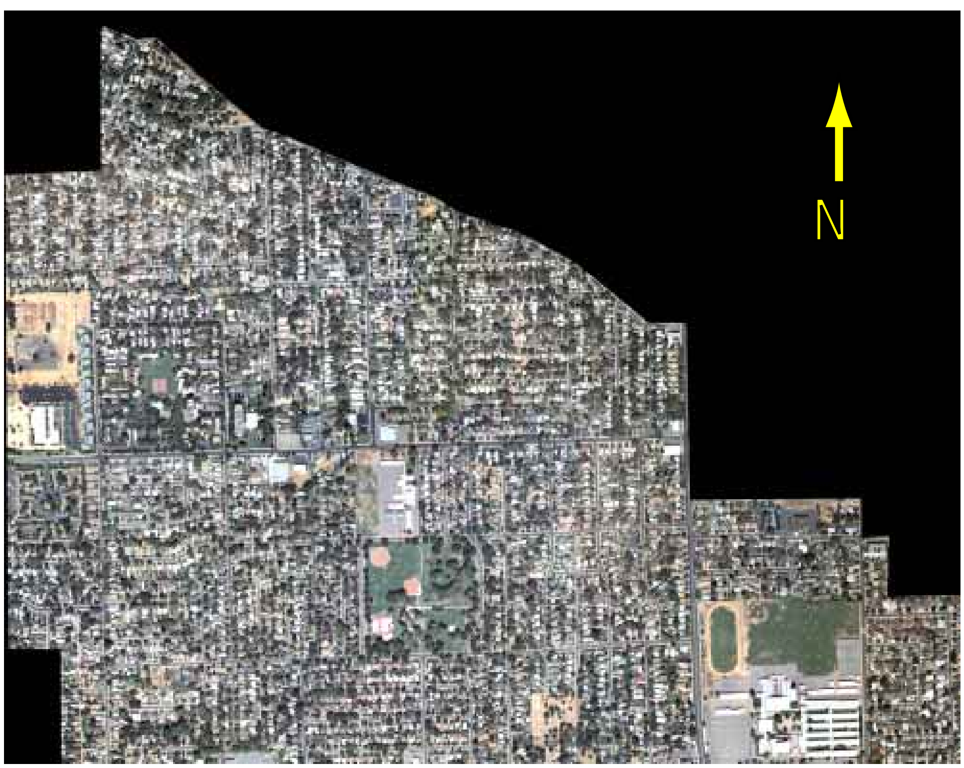


Figure 22. Aerial photo of Tahoe Park Area.

The results from the above-the-canopy perspective are given in Table 5 (row 5f). By surface-type percentages, this area is quite similar to the Jack Davis Park Area. The major difference between these two areas is the higher percentage of "Tree Cover" in this area. It is clear from the aerial photos that the trees in the Tahoe Park Area are more dense than those in the Jack Davis Park Area. It should be noted that these areas are located near each other, with only 0.5km (0.3 miles) of separation between them at their nearest points.

4.5.7 East Downtown Area (A high-density mixed neighborhood)

This area is east of 16th Street in downtown Sacramento. It is an older, high-density neighborhood of mixed use. The selected study area covered 2.8km^2 and included several parks, schools, offices, and shops. **Figure 23** shows the area actually analyzed in this task.

The above-canopy results are presented for this area in row 5g of Table 5. As indicated by the percentage of "Barren Land," this area is highly developed. The few points categorized as "Dry/Barren Land" are primarily around highways or railroad tracks. Also demonstrated in the table above, the "Tree Cover" in this area is higher than in the other residential areas. Table 6 (row g), gives the results from underneath the tree canopy. The tree cover in this area is so extensive that the surface-type under the canopy of the trees could not always be determined. Thus, most of the contents of the "Miscellaneous" category (75% under-the-canopy) derives from the category "Tree Covering Other". This category is intended for surfaces under the tree canopy that can be identified but are not explicitly listed in one of the other "tree" categories. In this area and other heavily treed areas the "Tree Covering Other" category also includes the percentages of the surface-types under the canopy that cannot be identified. Therefore, the percentage of surfaces classified as "Miscellaneous" is in this case quite high.

Percentages of the man-made surfaces, roofs and roads are higher here than in the other residential areas. This reflects how fully this particular area is developed. Even with these high percentages of man-made surfaces, approximately 34% of the area is covered by vegetation from an above-the-canopy perspective. This is comparable to the percentage of vegetated areas in the nearby "Downtown Sacramento and City Center Area" discussed previously. As mentioned in the discussion of the city center area, this heavily forested city should not be considered typical of other American cities.

4.5.8 Carmichael Area (An older neighborhood with schools and parks)

This is an older area consisting primarily of single-family detached homes, schools, and parks. It is located northeast of downtown. **Figure 24** shows the area actually analyzed in this task. The visible portion of this photo covers 1.7km^2.

The above-canopy results are presented for this area in row 5h of Table 5. The percentage of vegetated areas from the above-the-canopy perspective is approximately 50%. This is the highest vegetated coverage present in any of the residential areas studied. As shown in Figure 24, trees are scattered throughout the residential neighborhood and are both numerous and mature. Following are the results of the analysis from an under-the-canopy perspective.

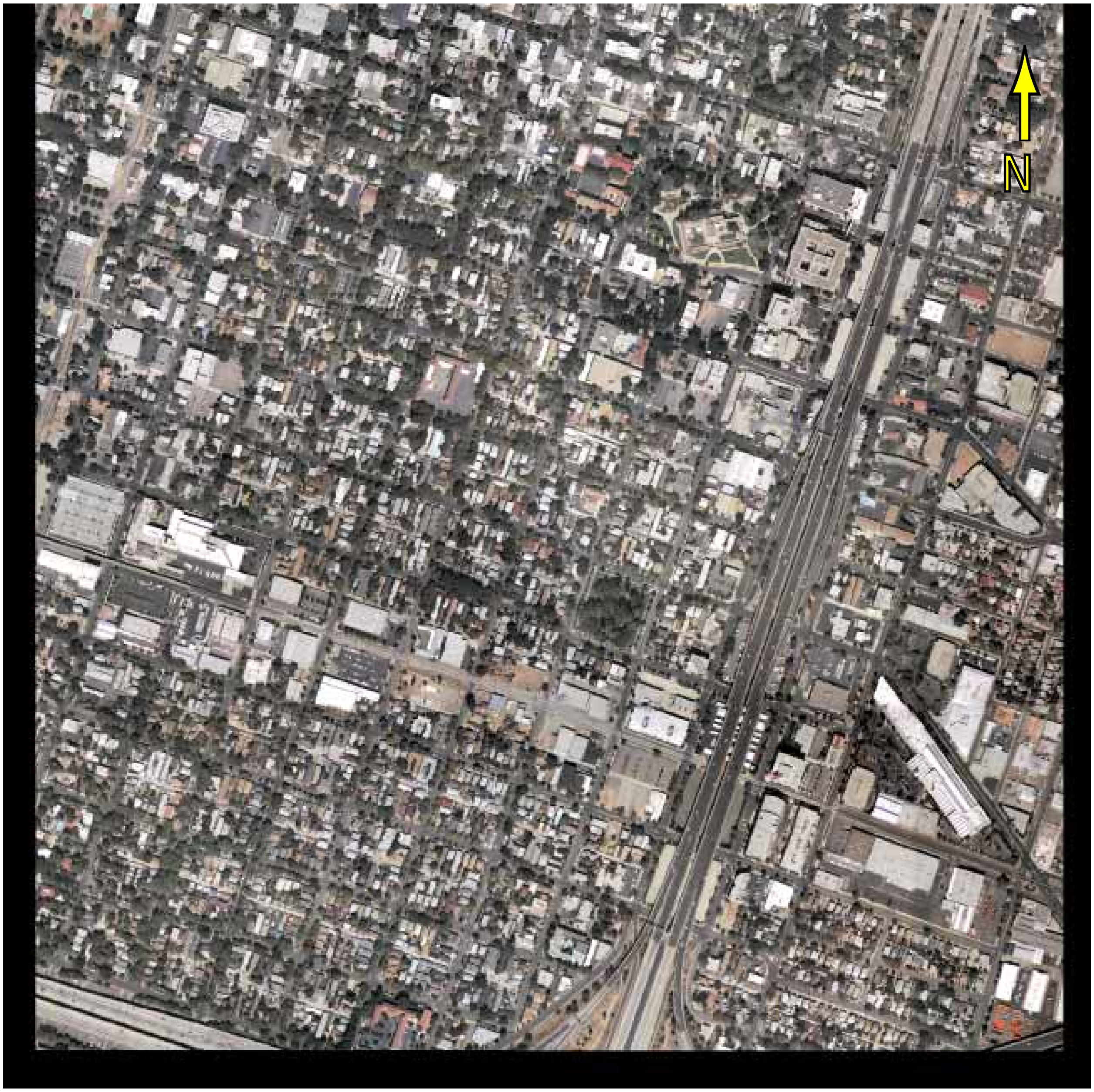


Figure 23. Aerial photo of East Downtown Area.

Figure 24. Aerial photo of Carmichael Area.

This area is highly developed, with the "Barren Land" percentage being mostly representative of utilized areas around houses or schools that do not have grass planted or maintained on them. The Carmichael area is similar to the Tahoe Park area in its high percentages of both vegetation and man-made surfaces as well as in its homogeneous use (predominantly single-family homes).

4.6. Summary

The results of this analysis are summarized in **Figure 25** (above-the-canopy view of the city) and **Figure 26** (under the tree canopy). In downtown Sacramento, the top view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 30% of the area, whereas roofs cover 23% and paved surface (roads, parking areas, and sidewalks) 41%. The under-the-canopy fabric consists of 52% paved surfaces, 26% roofs, and 12% grass. In the industrial areas, vegetation covers 8-14% of the area, whereas roofs cover 19-23%, and paved surfaces 29-44%. The surface-type percentages in the office area were 21% trees, 16% roofs, and 49% paved surfaces. In commercial areas, vegetation covers 5-20%, roofs 19-20%, paved surfaces 44-68% (about 25-54% are parking areas). Residential areas exhibit a wide range of percentages among their various surface-types. On the average, vegetation covers about 36% of the area (ranging from 32% to 49%), roofs cover about 20% (ranging from 12% to 25%), and paved surfaces about 28% (ranging from 21% to 34%).

For residential areas, Myrup and Morgan (1972) estimated a fraction of roof area 23%, streets 22%, green areas 33% and *other impermeable* surfaces 22%. Their estimates for roofs and green surfaces compare fairly well with our estimates for roofs and vegetated areas. However, if we sum their estimates for streets and other impermeable surfaces and compare that figure to our estimate for paved surfaces, their estimate is much higher. Basically, Myrup and Morgan state that all the surfaces in a residential area are either roofs, green, or impermeable surfaces. Clearly, our aerial photos found that about 8% of residential surfaces should be included in *other* categories. The wide range of surface-type percentages in many of the land-use categories demonstrates their site-specific nature. Therefore, in most traditional land-use/land-cover classification systems, it is especially difficult to account for the variation between similar land-uses.

5. Extrapolation to Metropolitan Sacramento

Table 7 summarizes the assignments of the observed land-use categories (OLUC) in Sacramento to those of the USGS Land-Use/Land-Cover (LULC) categories. Since our aerial photos were mostly concentrated on urban areas, we have several samples of residential and commercial categories and only one sample each for industrial, industrial/commercial, and mixed urban or built-up land. For "transportation/communication" and "other mixed urban or built-up land," we were uncertain regarding which categories to map. Therefore, they remained unchanged.

The average characteristics of various LULC categories are listed in **Table 8.** We assumed that LULC categories 16 and 17 have similar characteristics. The USGS/LULC categories

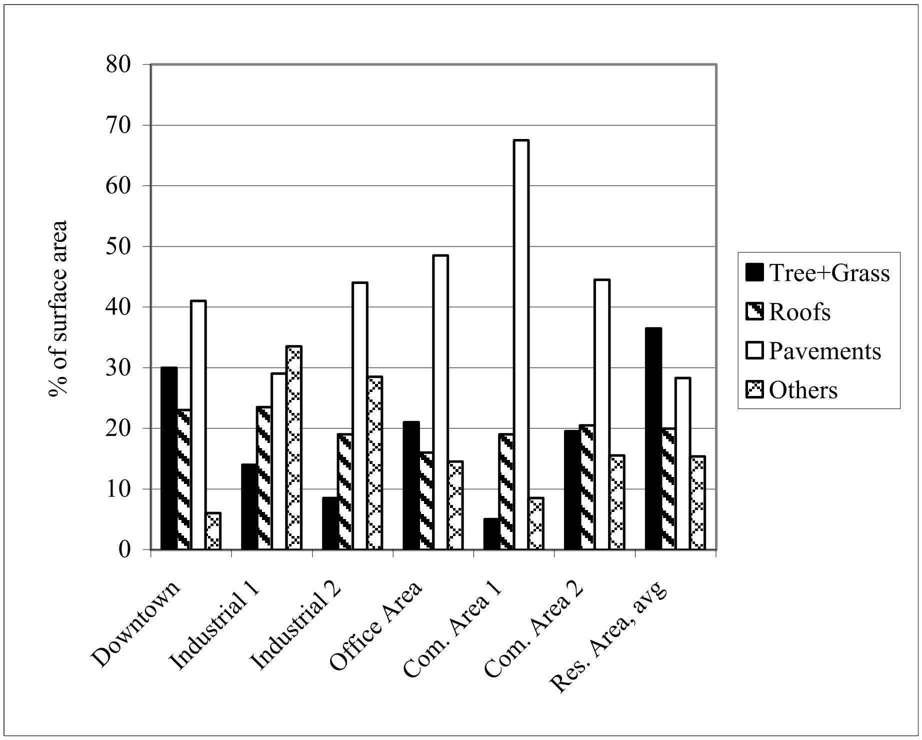


Figure 25. Above the Canopy Fabric of Sacramento, CA

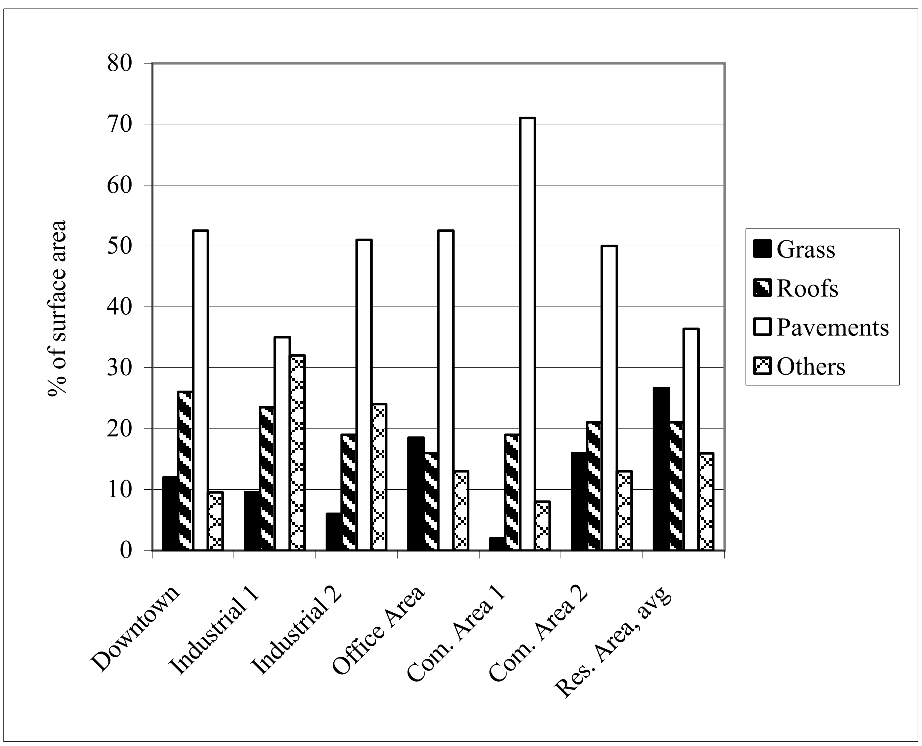


Figure 26. Under the Canopy Fabric of Sacramento, CA

Table 7. USGS/LULC description for urban area and related observed land-use categories (OLUC).

USGS/LULC	Description	OLUC Included
11	Residential	5a,5b,5c,5d,5e,5f,5h
12	Commercial/Service	1,3a,4a,4b
13	Industrial	2a
14	Transportation/Communications	NA
15	Industrial and Commercial	2b
16	Mixed Urban or Built-up Land	5g
17	Other Mixed Urban or Built-up Land	NA

Table 8. Calculated surface area percentages by USGS/LULC categories.

USGS/ LULC	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.
11	14.7	19.4	12.7	8.0	4.9	10.2	24.5	5.6
12	9.6	19.8	15.5	3.7	31.1	7.3	9.3	3.8
13	8.1	23.4	7.3	1.3	20.0	19.7	6.0	14.3
14	0.0	5.0	80.0	1.0	10.0	4.0	0.0	0.0
15	2.8	19.2	10.3	1.3	32.1	15.6	5.6	13.1
16	26.8	23.7	17.6	4.5	9.5	2.1	7.1	8.7
17	26.8	23.7	17.6	4.5	9.5	2.1	7.1	8.7

Table 9. Total surface areas (km^2) in metropolitan Sacramento (by Category).

USGS/ LULC	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.	Total
11	58.6	77.4	50.7	31.9	19.5	40.7	97.7	22.3	398.9
12	13.2	27.3	21.4	5.1	42.9	10.1	12.8	5.2	138.1
13	4.7	13.6	4.2	0.8	11.6	11.4	3.5	8.3	58.1
14	0.0	4.6	73.9	0.9	9.2	3.7	0.0	0.0	92.4
15	0.1	0.4	0.2	0.0	0.7	0.3	0.1	0.3	2.2
16	11.3	10.0	7.4	1.9	4.0	0.9	3.0	3.7	42.0
17	20.6	18.2	13.6	3.5	7.3	1.6	5.5	6.7	77.0
Total Urban Area	108.5	151.5	171.4	44.1	95.3	68.7	122.6	46.5	808.6
Total Non-Urban Area									17079.6

presented in Table 8 are summarized in **Figure 27a**. The data clearly indicate that about half of the 800km^2 analyzed in this study is residential. Commercial service and industrial areas taken together constitute another 25% of the total area.

The areas for each LULC categories for the entire simulations domain of 172km by 104km were then calculated (See **Table 9**). Of the total domain area of approximately 18,000km^2, about 808km^2 is categorized as urban area of which approximately half is residential. The total roof area as seen above the canopy comprises about 19% of the urban area (about 150km^2), total paved surfaces (roads, parking areas, sidewalks) comprises 39% (about 310km^2), and total vegetated area about 28% (230km^2) (see **Figure 27b**). The actual total roof area as seen under the canopy comprises about 20% of the urban area (about 160km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) comprises 45% (about 360km^2), and total vegetated area (only grass and bushes) about 20% (160km^2) (see **Figure 27c**).

Sacramento is a fairly green city, but the potential for additional urban vegetation is large. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, 30% of parking areas, they would add up to about an additional 15% tree cover for the entire city. An additional tree cover of 15% is about 120km^2 of the urban area. Assuming that an average tree can have a horizontal cross-section of about 50m^2, these calculations suggest a potential for an additional 24 million trees in Sacramento. As climate and air-quality simulations have indicated, 24 million additional trees can have a significant impact on cooling Sacramento and improving ozone air quality.

The potential for increasing the albedo of Sacramento is also very large. Impermeable surfaces (roofs and pavements) comprises about 56% of the total area of Sacramento. For illustration proposes, we calculate potentials for changing the albedo of Sacramento, assuming two different scenarios. One scenario assumes a modest change in the albedo of impermeable surfaces, the other assumes an aggressive increase in albedo of all surfaces. These scenarios are summarized in **Table 10**. The resulting change in the albedo of the city is summarized in **Table 11**. Under the low-albedo scenario, the overall residential and commercial albedo is changed by 5.4% and 11.3% respectively; the average albedo of the city is increased by 8.2%. For the high-albedo scenario, the overall albedo of residential and commercial areas change by 11.8% and 20.3%, and the average albedo of the city is increased by 15.8%. Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

These example are used for illustration purposes only. For climate and air-quality simulations where both albedo and vegetation are changed, the overall changes in albedo and vegetation differ from these calculations.

6. Discussions and Recommendations for Flights Over Other Cities

This report focuses on the characterization of the fabric of a region in terms of surface-type makeup. The data obtained from the Sacramento flights suggest that it is possible to characterize the fabric of a region of interest accurately and cost-effectively. However, depending on the

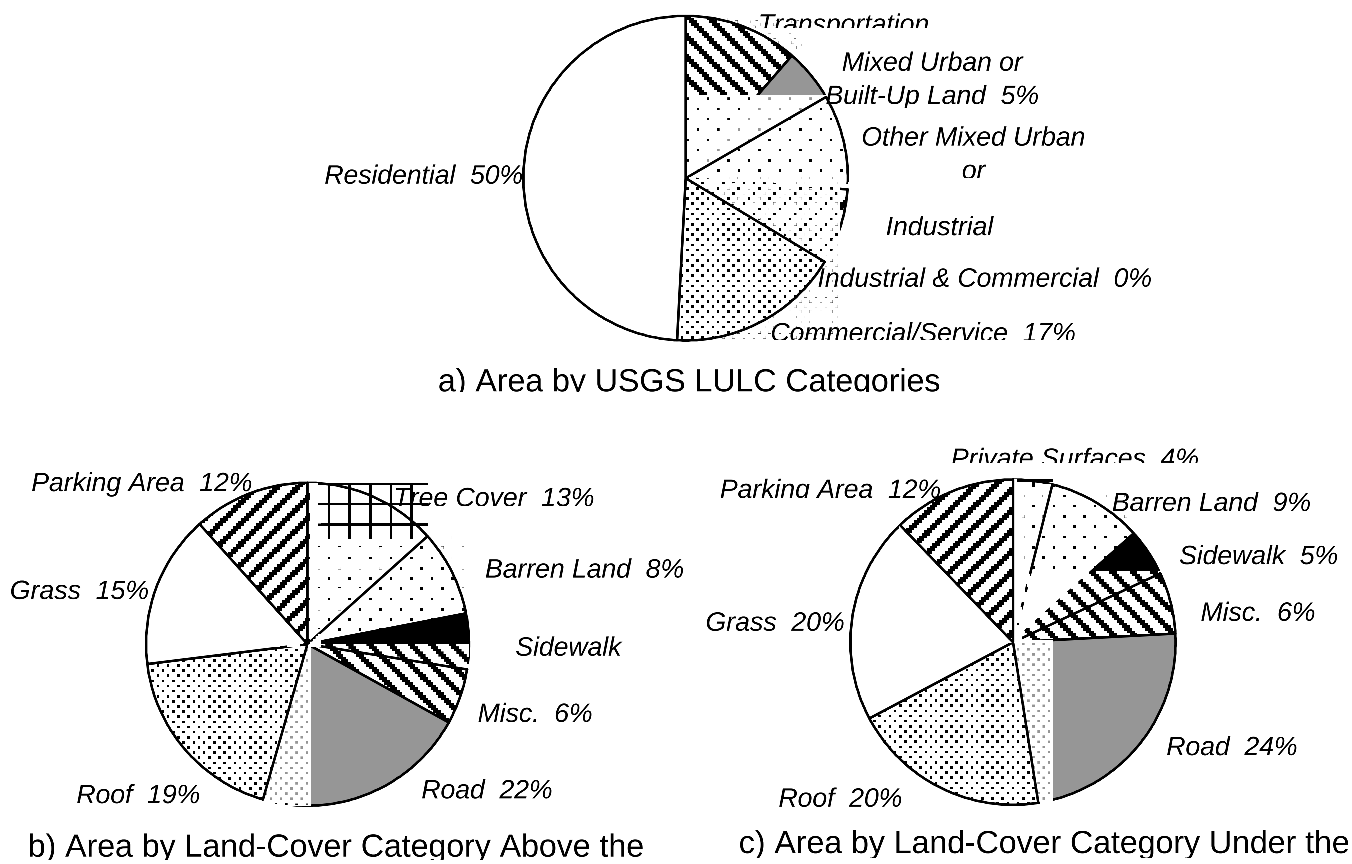


Figure 27. Land-use/land-cover of the entire developed area of Sacramento, CA.

Table 10. Two albedo modification scenarios.

Surface-Type	High-Albedo Change	Low-Albedo Change
Residential Roofs	0.3	0.1
Commercial Roofs	0.4	0.2
Roads	0.25	0.15
Parking Areas	0.25	0.15
Sidewalks	0.2	0.1

Table 11. Net change in the albedo of Sacramento for high- and low-albedo scenarios.

Area	High-Albedo Scenario	Low-Albedo Scenario
Residential	0.118	0.054
Commercial/Service	0.203	0.113
Industrial	0.164	0.089
Transportation/Communications	0.247	0.146
Industrial and Commercial	0.185	0.103
Mixed Urban or Built-up Land	0.160	0.081
Other Mixed Urban or Built-up Land	0.172	0.093
Average over the Entire Area	0.158	0.082

purpose of the application and the funds available, a separate decision must be made for each UHIPP city or region as to the most appropriate combination of data, i.e., a combination of aerial photographs, USGS/LULC, and satellite/aircraft data such as ATLAS or AVHRR.

Based on this case study, it is estimated that in a city the size of Sacramento between 10 and 50 square km of aerial photography would suffice. At a rate of $140 per square km, the total cost of the flight and data would amount to about $7000 at most. This assumes that some extrapolation to region-wide scale, as mentioned in section 5, will be needed.

In addition, the companies that perform this type of data collection are flexible in dealing with and designing flight paths and selecting flight times. This allows for better planning of the flight track and its timing so as to minimize shadows and focus on areas of interest, e.g., specific land-uses or covers. In light of this experience with the Sacramento flights, this process is recommended for the other two cities under the EPA’s UHIPP, i.e., Baton Rouge and Salt Lake City. This process is also recommended for any city interested in implementing heat-island reduction strategies or in modeling their meteorological and air-quality aspects.

7. Conclusions

To estimate the impact of light-colored surfaces (roofs and pavements) and urban vegetation (trees, grass, shrubs) on the meteorology and air quality of a city, it is essential to accurately characterize various urban surfaces. Of particular importance is the characterization of the area fraction of various surface-types and vegetative fraction. In this report, a method for developing data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color photography is discussed. We devised a semi-automatic Monte-Carlo method to sample the data and visually identify the surface-type for each pixel. The color aerial photographs for Sacramento covered a total of about 65 square km (25 square miles). At 0.30-m resolution, there were approximately 7×10^8 pixels of data available for analysis.

Results from this analysis suggest several possible land-use and surface-type classifications for the Sacramento area. We examined five major land-use types: 1) downtown and city center, 2) industrial, 3) offices, 4) commercial, and 5) residential. For each of these land-uses, up to 30 different surface-types were identified and their fractional areas computed. Results were tabulated in various parts of this report. In addition, a method was devised to extrapolate these results from neighborhood to metropolitan scales. The method relies on using land-use/land-cover data from the USGS to map the area distributions.

In downtown Sacramento, the top view (above the canopy) shows that vegetation covers 30% of the area, whereas roofs cover 23% and paved surfaces (roads, parking areas, and sidewalks) 41%. The under-the-canopy fabric consists of 52% paved surfaces, 26% roofs, and 12% grass. In the industrial areas, vegetation covers 8-14% of the area, whereas roofs cover 19-23%, and paved surfaces 29-44%. The surface-type percentages in the office area were 21% trees, 16% roofs, and 49% paved surfaces. In commercial areas, vegetation covers 5-20%, roofs 19-20%, paved surfaces 44-68% (about 25-54% of parking areas). Residential areas exhibit a wide range of percentages among their various surface-types. On the average, vegetation covers about 36% of the area (ranging from 32 to 49%), roofs about 20% (12-25%), and paved surfaces about 28% (21-34%). Trees mostly shade the streets, parking lots, grass, and sidewalks. Under the canopy, the percentage of paved surfaces is significantly higher. In most non-residential areas, paved surfaces cover 50-70% of the area. In residential areas, on the average, paved surfaces cover about 35% of the area.

Land-use/land-cover (LULC) data from the USGS was used to extrapolate these results from neighborhood scales to metropolitan Sacramento. For an area of roughly $800 km^2$, defining most of metropolitan Sacramento, about half is residential. The total roof area as seen above the canopy comprises about 19% of the urban area (about $150 km^2$), total paved surfaces (roads, parking areas, side walks) comprises 39% (about $310 km^2$), and total vegetated area about 28% ($230 km^2$). The actual total roof area as seen under the canopy comprise about 20% of the urban area (about $160 km^2$), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) 45% (about $360 km^2$), and total vegetated area (only grass and bushes) about 20% ($160 km^2$).

Sacramento is a fairly green city, but the potential for additional urban vegetation is large. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, 30% of parking areas, they would add up to about 15% in additional tree cover for the entire city. An additional tree cover of 15% amounts to about 120km^2 of the urban area. Assuming that an average tree can have a horizontal cross-section of about 50m^2, these calculations suggest potential for 24 million additional trees in Sacramento. As climate and air-quality simulations have indicated, 24 million additional trees can have a significant impact on cooling Sacramento and improving ozone air quality.

The potential for increasing the albedo for Sacramento is also very large. Impermeable surfaces (roofs and pavements) comprise about 56% of the total area of Sacramento. For illustration proposes, if we assume that the albedo of the residential roofs can increase by 0.2, commercial roofs by 0.3, roads and parking areas by 0.15, and sidewalks by 0.1, the albedo of Sacramento can then be increased by about 0.16 (16%). Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

These results are based on a limited analysis for one city. In Sacramento, there is a significant variation in the fabric of the neighborhoods selected for this analysis. Although an attempt was made to select neighborhoods that represent many different variations in the overall communities, these results should not be extrapolated to other cities and regions. Many cities are unique in terms of land-use patterns and constructions (e.g. most urban homes on the west coast are single-story as opposed to two-story houses in the east). It is recommended that a similar analysis for several other cities in different regions of the country be performed in order to expand our understanding of the fabric of the city. The next step should be to expand this effort in order to obtain data for other UHIPP cities, such as Salt Lake City, Chicago, and Baton Rouge.

References

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Appendix A.

Automatic Outlining of Pavements, Roofs, and Green Areas

In this section, a method is described to facilitate the outlining of surface-types, specifically, roofs, trees, and pavements. This method is based on discerning the deviation of R-G-B counts at any given point with respect to the counts at a reference point. In this case, the reference point is a marching one; that is, there is one centers for every nine pixels at a time. The method is an integral part of the ERDAS/Imagine software and allows the user to specify the degree of detail at which to perform the discrimination test. For example, if the user decides to use a square of 3 x 3 pixels (each pixel is 0.30 m), the method will select the central pixel as a reference and carry out the discrimination test on each of the 8 surrounding pixels by comparing the deviation in their R-G-B counts from those of the central one. Then the next 9 pixels are selected and the process repeated until the entire photo area designated by the user has been analyzed.

The calculation of the three-dimensional (RGB) deviation of counts is done according to the Mean Euclidean Distance (MED) defined as:

$$\mathrm{MED} = \frac{\sum \left\{ \sum_{\lambda} (X_{c\lambda} - X_{ij\lambda})^2 \right\}^{1/2}}{n - 1}$$

where x is the value (count) at a wavelength λ for the central, reference pixel (c) or location (i,j), and n is the number of samples. The discrimination test can also be done using the statistical variance of the R-G-B bands from those of the central pixel—similar to MED.

A result of such a procedure is shown in Figure 6. Outlines of roofs, vegetation, and pavements are clearly visible. However, the procedure has so far failed in distinguishing between, e.g., driveways and parking lots, or streets and driveways. But one cannot realistically expect that these land-use differences be detected by a simple procedure relying only on R-G-B deviations, although this procedure is useful in performing a first-cut screening of various surface and green types.